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GREENGUIDE FOR SUSTAINABLE ENERGY EFFICIENT REFRIGERATED STORAGE FACILITIES

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Renewable Energy Technologies
- Transportation

GreenGuide for Sustainable Energy Efficient Refrigerated Storage Facilities is the final report for the GreenGuide for Sustainable Energy Efficient Refrigerated Storage Facilities project (contract number PIR-08-011) conducted by Becker Engineering Company. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

A green, sustainable, energy efficient, cost-effective refrigerated storage facility is defined as a structure that maintains a safe and appropriate environment for the storage of perishable food items while limiting its impact on the Earth's natural resources, including both energy and water. The design, construction, retrofit and operation of a green refrigerated storage facility requires knowledge of a wide range of complex issues. The goal of this project was to realize increased energy conservation and environmental stewardship in the refrigerated warehouse industry through the development of a comprehensive best practices "GreenGuide" that provided engineers, contractors, owners and operators with information concerning the design, construction, retrofit and operation of green, sustainable, energy efficient, refrigerated facilities.

A green refrigerated storage facility should employ simple, passive design and engineering solutions to achieve this end where possible. The refrigeration loads of such a facility should be reduced to the minimum needed to maintain a safe environment for the storage of perishable food items. Its refrigeration equipment should be designed and constructed to be robust, reliable, maintainable and flexible and should operate at high energy efficiency. The facility should be constructed of sustainable materials. The facility's refrigerant should be environmentally friendly with low ozone depletion potential and low global warming potential as compared to other refrigerants that can perform the same function with the same annual energy consumption.

The GreenGuide provided guidance on how to participate effectively on teams charged with designing, constructing and/or retrofitting green storage facilities and provided an understanding of the technical issues regarding high-performance integrated systems design and operation.

Keywords: Green, sustainable, energy efficient, cost-effective, refrigerated storage facility, refrigerant, refrigerated warehouse industry, best practices guide, design, construction, retrofit, operation, high-performance integrated systems design, refrigeration equipment

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EXECUTIVE SUMMARY

Introduction

Agriculture is a major industry in California that generated revenues of \$43.5 billion in 2011. California is also the leading producer of fruits and vegetables in the United States. The processing of these fruits and vegetables creates about \$50 billion of added value for California per year and produces more than 1.8 billion pounds of frozen products every year. Most perishable commodities must be refrigerated soon after harvest. Many food products require cooling and freezing soon after they are processed. Refrigerated warehouses are an essential part of the agricultural industry in California.

Project Purpose

For the purposes of this project, a green, sustainable, energy efficient, cost-effective refrigerated storage facility is defined as a structure that maintains a safe and appropriate environment for the storage of perishable food items while limiting its impact on the Earth's natural resources, including both energy and water. Such a facility should employ elegant, simple, passive design and engineering solutions to achieve this end where possible.

The goal of this project was to realize increased energy conservation and environmental stewardship in California's refrigerated warehouse industry through the development of a comprehensive best practices "GreenGuide" to provide California's engineers, contractors, owners and operators with practical information to facilitate the design, construction, retrofit and operation of green, sustainable, energy efficient, cost-effective refrigerated facilities for the storage of perishable food items.

Project Results

The annual refrigeration loads of a green, sustainable, energy efficient, cost-effective refrigerated storage facility should be reduced to the minimum needed to maintain a safe and appropriate environment for the storage of perishable food items. The equipment that removes these loads should be designed and constructed to be robust, reliable, maintainable with minimal effort and flexible with respect to changes in facility function and future improvements in technology. These characteristics will be measured by the system's annual cost of maintenance and its years of service life. The equipment should operate at high energy efficiency, as measured by its annual energy consumption.

A green, sustainable, energy efficient, cost-effective refrigerated storage facility should be constructed of sustainable materials as measured by their toxicity, their recycled content and their cost of recycling after they no longer serve their original purposes. The facility's refrigerant should be environmentally friendly with low ozone depletion potential and low global warming potential as compared to other refrigerants that can perform the same function with the same annual energy consumption.

The design, construction, retrofit and operation of a green, sustainable, energy efficient, cost-effective refrigerated storage facility requires knowledge and understanding of a wide range of complex issues. Information about sustainable refrigerated storage facilities was not readily

accessible and was scattered throughout various publications by equipment manufacturers, engineering and design firms, and professional organizations.

The GreenGuide provided guidance on how to participate effectively on teams charged with designing, constructing and/or retrofitting green storage facilities and provided an understanding of the technical issues regarding high-performance integrated systems design and operation. The GreenGuide focused on single story, multi-temperature, multi-segmented refrigerated storage facilities of 50,000 square feet (ft²) or greater. An extensive industrial survey of refrigeration engineers, contractors, equipment manufacturers, owners, operators, and trade and professional organizations as well as a comprehensive literature review provided information on current, state-of-the-art green technologies and practices applicable to the design, construction, retrofit and operation of green, sustainable, energy efficient, cost-effective cold storage facilities. The GreenGuide summarized and organized this information. The GreenGuide also summarized the results of various studies performed by owners and operators, engineering organizations and universities concerning green, sustainable, energy efficient, cost-effective refrigerated warehouses.

The GreenGuide targeted California's refrigerated storage facility designers, engineers, contractors, facility owners, and facility operations and maintenance personnel. The GreenGuide addressed the construction and operation of new, green, sustainable, energy efficient, cost-effective refrigerated storage facilities as well as the sustainable retrofitting and operation of existing facilities. The sustainable retrofitting and operation of existing facilities was a large market segment in California and provided an additional significant sustainability and energy efficiency benefit to the electricity ratepayers in California.

An outreach program was developed to disseminate the information contained in the GreenGuide to engineers, owners and operators in California. Short courses and seminars were developed that facilitated the design, construction, retrofit and operation of green, sustainable, energy efficient, cost-effective refrigerated storage facilities in California.

Project Benefits

According to the United States Department of Agriculture (USDA), at the time this report was written California had 267 refrigerated warehouses with an estimated total storage volume of 548 million cubic feet (ft³) and a total refrigeration load of about 120,000 tons of refrigeration. This resulted in electric power consumption of about 360 megawatts (MW). The authors concluded it was reasonable to assume that a five percent reduction in power demand (18 MW) could be achieved through implementing the measures described in the GreenGuide. On an annual basis this would amount to an energy savings of 158 gigawatt hours (GWh) of electricity per year. Another estimate on refrigerated warehouses was provided by the International Association of Refrigerated Warehouses (IARW). IARW estimated that the refrigerated warehouses in California consume one terrawatt (TWh) of electricity per year. Based on this estimate the authors believed it was reasonable to assume that a five percent reduction in energy consumption of 50 GWh per year could result from implementing the findings of this project. California electricity ratepayers will therefore reap significant benefits from the energy

conservation and environmental stewardship measures for California's refrigerated warehouse industry described in the *GreenGuide for Sustainable Energy Efficient Refrigerated Storage Facilities*.

CHAPTER 1: Introduction

Agriculture is a major industry in California that generated revenues of \$43.5 billion in 2011 (CDFA 2013). California is also the leading producer of fruits and vegetables in the United States. The processing of these fruits and vegetables creates about \$50 billion of added value for California per year. According to the California Institute for Food and Agricultural Research (CIFAR), this industry produces more than 1.8 billion pounds of frozen products every year (CIFAR 2004).

The preservation of food is the origin of the refrigeration industry and, by far, it's most significant application. The cooling and freezing of food effectively reduces the activity of micro-organisms and enzymes, thus slowing deterioration. In addition, crystallization of water reduces the amount of liquid water in the food item and inhibits microbial growth. Perishable food storage requirements, including temperature, humidity and acceptable storage life, vary according to food type (Becker and Fricke 1999a, 1999b; Fricke and Becker 2004; Fricke and Becker 2006).

Most perishable commodities must be refrigerated soon after harvest. Many food products require cooling and freezing soon after they are processed. Thus, refrigerated warehouses are an essential part of the agricultural industry in California, and due to the large amount of food crops grown and processed in California, refrigerated warehouses are significant consumers of electrical energy in California. In fact, it has been estimated that refrigerated warehouses are responsible for 20 percent of the total electric energy consumption of the food industry in California (CIFAR 2004).

The United States Department of Agriculture (USDA) reports that California has 267 refrigerated warehouses with an estimated total storage volume of 548 million ft³ (USDA 2012). Furthermore, the International Association of Refrigerated Warehouses (IARW) estimates that the refrigerated warehouses in California consume 1 TWh (1000 GWh) of electricity per year (CIFAR 2004). Therefore, California electricity ratepayers will reap significant benefits from the energy conservation and environmental stewardship measures for California's refrigerated warehouse industry described in this *GreenGuide for Sustainable Energy Efficient Refrigerated Storage Facilities*.

1.1 Background and Motivation

1.1.1 A Green, Sustainable, Energy Efficient Refrigerated Storage Facility

For purposes of this document, a green, sustainable, energy efficient, cost-effective refrigerated storage facility is defined as a structure that maintains a safe and appropriate environment for the storage of perishable food items while limiting its impact on the Earth's natural resources including both energy and water. Where possible, such a facility will employ elegant, simple, passive design and engineering solutions to achieve this end.

The annual refrigeration loads of a green, sustainable, energy efficient, cost-effective refrigerated storage facility will be reduced to the minimum needed to maintain a safe and appropriate environment for the storage of perishable food items. The equipment which removes these loads will be designed and constructed to be robust, reliable, maintainable with minimal effort and flexible with respect to changes in facility function and future improvements in technology. These characteristics will be measured by the system's annual cost of maintenance and its years of service life. The equipment will operate at high energy efficiency, as measured by its annual energy consumption.

A green, sustainable, energy efficient, cost-effective refrigerated storage facility will be constructed of sustainable materials, as measured by their toxicity, their recycled content and their cost of recycling after they no longer serve their original purposes. The facility's refrigerant will be environmentally friendly with low ozone depletion potential and low global warming potential as compared to other refrigerants which can perform the same function with the same annual energy consumption.

1.1.2 Refrigerated Facility Definitions

Many terms are used to describe refrigerated buildings used to cool product or to keep the product cool. Commonly used terms and their definitions are as follows (IPENZ 2009):

- Chiller: Used to lower product temperature or remove heat from the product. Typically, chillers operate from 0°C to 10°C.
- Coolstore: Used to hold product temperatures in a range from 0°C to 10°C.
- Freezer: Used to freeze products or remove heat from the product and change the phase of the water contained in the product. Typically, freezers operate from -40°C to 0°C.
- Coldstore: Used to keep product temperature in a range from -30°C to 0°C.

1.1.3 Refrigerated Storage Capacity in the US and California

The gross refrigerated storage capacity in the US totaled about 90.9 million m³ in 2006 (Prakash and Singh 2008). From this, the actual volume used for storing commodities, or the usable refrigeration capacity, was 73.1 million m³. The usable freezer storage space, where temperatures are less than –18°C (0°F), comprises about 78 percent of this space and the remainder is usable cooler space, where temperatures are between –18°C and 10°C (0°F and 50°F). In California, there are a total of 267 refrigerated warehouses with a combined usable storage space of 9.1 million m³ and a total refrigeration load of about 120,000 tons of refrigeration. This results in an electric power consumption of about 360 MW (Prakash and Singh 2008).

1.1.4 Energy Consumption of Refrigerated Storage Facilities

Prakash and Singh (2008) compiled the results of the few published studies available regarding energy use among refrigerated warehouses in different parts of the world. These reports are based on surveys and they utilize the Specific Electricity Consumption (SEC) value to represent the energy efficiency of a warehouse. The SEC is defined as:

$$SEC = \frac{Annual\ Energy\ Consumption\ (kWh)}{Storage\ Volume\ (m^3)} \tag{1}$$

The results of these studies from Europe, New Zealand and the US show that the SEC value can vary greatly from 19 kWh/m³ to 124 kWh/m³ (Prakash and Singh 2008).

The energy benchmarking study of refrigerated warehouses by Prakash and Singh (2008) resulted in the following conclusions:

- Lighting affects the SEC value substantially. By using 20 percent more efficient lighting, the SEC value can be reduced by approximately 10 percent.
- Product thermal energy can affect the SEC value substantially. Food products should be brought into the storage facility at the same temperature of the storage rooms.
- Compared to other thermal energy loads, the infiltration energy load is usually small, contributing less than 5 percent to the SEC value.

According to Duiven and Binard (2002), the SEC of existing refrigerated storage facilities ranges between 30 and 50 kWh/m³ per year, depending upon the quality of the building, type of storage (chilled or frozen), room size, stock turnover, temperature of incoming product, and outside temperature. In addition, the electrical energy consumption for blast freezing of food products can range between 70 to 130 kWh per ton of product, while for plate freezing, the energy consumption can range between 60 to 100 kWh per ton (Duiven and Binard 2002).

The main energy end-uses within a refrigerated storage facility include product refrigeration, lighting, HVAC, manufacturing processes and forklift battery charging (Lekov et al. 2009). As shown in Figure 1, refrigeration accounts for over half of the energy use of a typical warehouse. If electric defrost is used in the refrigerated storage facility, it also contributes significantly to the overall energy use of the facility.

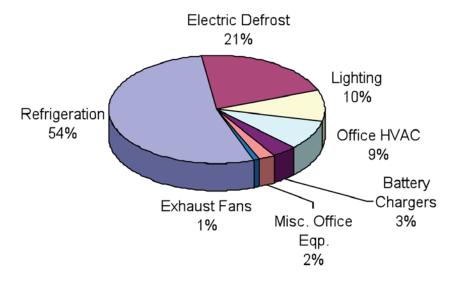


Figure 1: Energy End Use in Refrigerated Storage Facilities.

Source: (National Grid 2004)

1.2 Purpose and Scope of the GreenGuide

1.2.1 Purpose

The design, construction, retrofit and operation of a green, sustainable, energy efficient, cost-effective refrigerated storage facility requires knowledge and understanding of a wide range of complex issues. Therefore, the purpose of this project is to realize increased energy conservation and environmental stewardship in California's refrigerated warehouse industry through the development of a comprehensive best practices 'GreenGuide' to provide California's engineers, contractors, owners and operators with practical information that will facilitate the design, construction, retrofit and operation of green, sustainable, energy efficient, cost-effective refrigerated facilities for the storage of perishable food items. The GreenGuide provides guidance on how to participate effectively on teams charged with designing, constructing and/or retrofitting green storage facilities and provides an understanding of the technical issues regarding high-performance integrated systems design and operation.

1.2.2 Scope

This GreenGuide focuses on single story, multi-temperature, multi-segmented refrigerated storage facilities of 50,000 ft² or greater. This GreenGuide is based on the results of an extensive industrial survey of refrigeration engineers, contractors, equipment manufacturers, owners, operators, and trade and professional organizations, as well as a comprehensive literature review. The industrial survey and the literature review yielded information on current, state-of-the-art green technologies and practices applicable to the design, construction, retrofit and operation of green, sustainable, energy efficient, cost-effective cold storage facilities. The GreenGuide also summarizes the results of various studies performed by owners and operators, engineering organizations and universities concerning green, sustainable, energy efficient, cost-effective refrigerated warehouses.

1.3 Intended Audience

1.3.1 Wide Audience

A wide audience of readers will find this GreenGuide of value, including owners, officers and regional managers of food processing companies; plant managers, production and operation managers, and maintenance managers at food processing and refrigerated storage facilities; corporate engineering staff at food processing companies; operators of refrigeration systems; utility efficiency program personnel; designers of refrigerated facilities; energy analysts; as well as contractors and vendors who serve the refrigerated storage facility market.

1.3.2 Targeted Audience

This GreenGuide is targeted at California's refrigerated storage facility designers, engineers, contractors, facility owners, and facility operations and maintenance personnel. The GreenGuide addresses the construction and operation of new, green, sustainable, energy efficient, cost-effective refrigerated storage facilities as well as the sustainable retrofitting and operation of existing facilities. The sustainable retrofitting and operation of existing facilities is

a large market segment in California and will provide an additional significant sustainability and energy efficiency benefit to the electricity ratepayers in California. In addition, the information presented in the guide is important for the efficient operation of green, sustainable, energy efficient, cost-effective refrigerated storage facilities and therefore is of value to facility owners and facility operations and maintenance personnel in California.

1.3.3 Personnel

Several groups of personnel are involved in the design and operation of cold storage facilities, including (IPENZ 2009):

- Owners
- Operators
- Insurers
- Design engineers
- Regulators
- End users (the consumers of products stored in the facility)
- Building and installation contractors
- Maintenance and emergency workers

1.4 Environmental Definitions

1.4.1 Environmental Impact

An environmental impact assessment (EIA) is an assessment of the possible positive or negative impacts that a proposed project may have on the environment, together consisting of the environmental, social and economic aspects.

Environmental issues are harmful aspects of human activity on the biophysical environment. Major current environmental issues include climate change, pollution, environmental degradation, and resource depletion.

Sustainability is the key to preventing or reducing the effect of environmental issues. There is now clear scientific evidence that humanity is living unsustainably, and that an unprecedented collective effort is needed to return human use of natural resources to within sustainable limits (Gismondi 2000; Millennium Ecosystem Assessment 2005). For humans to live sustainably, the Earth's resources must be used at a rate at which they can be replenished.

1.4.2 Sustainability

Sustainability in a general sense is the capacity to support, maintain or endure. Since the 1980s human sustainability has been related to the integration of environmental, economic, and social dimensions towards global stewardship and responsible management of resources.

The standard and most generally used definition of sustainability is attributed to Gro Harlem Brundtland, former Prime Minister of Norway, and Chairperson of the World Commission on Environment and Development. The Commission was established by the Secretary General of the United Nations in 1983, and delivered its report in 1987. The Commission's report, entitled

"Our Common Future," defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987).

1.4.3 Green

Green is a word that can have many different meanings, depending upon circumstances (Swift and Lawrence 2010). One of these is the greenery of nature: grass, trees, and leaves. It is this symbolic reference to nature that is the meaning of green in this publication.

Green does not completely encompass the full meaning of sustainability, which means maintaining ecological balance. Some characteristics of green design have no impact in terms of maintaining ecological balance, such as indoor environmental quality, an important element of green design but not of sustainable design. Many green design characteristics, such as reduced energy usage and pollution, do have positive long-term effects on ecological balance and, therefore, do fall within the realm of sustainability.

Swift and Lawrence (2010) define a green/sustainable design as one that minimizes the negative human impacts on the natural surroundings, materials, resources, and processes that prevail in nature. They also define a green/sustainable building design as one that achieves high performance, over the full life cycle, in the following areas:

- Minimizing natural resource consumption through more efficient utilization of nonrenewable natural resources, land, water, and construction materials, including utilization of renewable energy resources to achieve net zero energy consumption.
- Minimizing emissions that negatively impact our indoor environment and the atmosphere of our planet, especially those related to indoor air quality (IAQ), greenhouse gases, global warming, particulates, or acid rain.
- Minimizing discharge of solid waste and liquid effluents, including demolition and occupant waste, sewer, and stormwater, and the associated infrastructure, required to accommodate removal.
- Minimizing negative impacts on site ecosystems.
- Maximizing quality of indoor environment, including air quality, thermal regime, illumination, acoustics/noise, and visual aspects to provide comfortable human physiological and psychological perceptions.

1.4.4 ASHRAE Standard 189.1

ASHRAE Standard 189.1-2011, Standard for the Design of High-Performance Green Buildings (ASHRAE 2011b), addresses site sustainability, water use efficiency, energy efficiency, indoor environmental quality (IEQ), and the building's impact on the atmosphere, materials and resources. It is intended that ASHRAE Standard 189.1-2011 will be used in conjunction with ASHRAE Standard 90.1-2010, Energy Standard for Buildings Except Low-Rise Residential Buildings (ASHRAE 2010d), ASHRAE Standard 62.1-2010, Ventilation for Acceptable Indoor Air Quality (ASHRAE 2010c) and ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy (ASHRAE 2010b).

ASHRAE Standard 189.1-2011 provides minimum requirements for the siting, design, construction and plan for operation of high-performance, green buildings. The intent is to balance environmental responsibility, resource efficiency, occupant comfort and well-being, and community sensitivity while supporting the goal of development that meets the needs of the present without compromising the ability of future generations to meet their own needs. ASHRAE Standard 189.1-2011 applies to new buildings and their systems, new portions of buildings and their systems, and new systems and equipment in existing buildings. The standard does not apply to single-family houses, multi-family structures of three stories or fewer above grade, and manufactured houses.

1.4.5 Ozone Depletion Potential

The ozone depletion potential (ODP) of a chemical compound is the relative amount of degradation to the ozone layer it can cause, as compared with trichlorofluoromethane (R-11 or CFC-11) being fixed at an ODP of 1.0 (Pyle et al. 1991). That is, the ODP of a given substance is defined as the ratio of the global loss of ozone due to a given mass of the substance over the global loss of ozone due to the same mass of R-11. Of the halocarbons, R-11 has the maximum ODP because of the presence of three chlorine atoms in the molecule.

Ozone depletion describes two distinct but related phenomena observed since the late 1970s: a steady decline of about 4 percent per decade in the total volume of ozone in Earth's stratosphere (the ozone layer), and a much larger springtime decrease in stratospheric ozone over Earth's polar regions. The latter phenomenon is referred to as the ozone hole. In addition to these well-known stratospheric phenomena, there are also springtime polar tropospheric ozone depletion events.

The details of polar ozone hole formation differ from that of mid-latitude thinning, but the most important process in both is catalytic destruction of ozone by halogens. The main source of these halogen atoms in the stratosphere is photodissociation of man-made halocarbon refrigerants. These compounds are transported into the stratosphere after being emitted at the surface. Both types of ozone depletion were observed to increase as emissions of halocarbons increased. CFCs and other contributory substances are referred to as ozone-depleting substances (ODS).

Since the ozone layer prevents most harmful UVB wavelengths (280–315 nm) of ultraviolet light (UV light) from passing through the Earth's atmosphere, observed and projected decreases in ozone have generated worldwide concern leading to adoption of the Montreal Protocol that bans the production of CFCs, halons, and other ozone-depleting chemicals such as carbon tetrachloride and trichloroethane. It is suspected that a variety of biological consequences such as increases in skin cancer, cataracts, damage to plants, and reduction of plankton populations in the ocean's photic zone may result from the increased UV exposure due to ozone depletion (Dobson 2005).

1.4.6 Montreal Protocol

The Vienna Convention for the Protection of the Ozone Layer is a multilateral environmental agreement that was written at the Vienna Conference of 1985 and entered into force in 1988. It

has been ratified by 197 states (all United Nations members as well as the Holy See, Niue and the Cook Islands) as well as the European Union (United Nations 1985). It acts as a framework for the international efforts to protect the ozone layer. However, it does not include legally binding reduction goals for the use of CFCs, the main chemical agents causing ozone depletion. These are laid out in the accompanying Montreal Protocol.

In 1985 the Vienna Convention established mechanisms for international co-operation in research into the ozone layer and the effects of ozone depleting chemicals (ODCs). 1985 also marked the first discovery of the Antarctic ozone hole. On the basis of the Vienna Convention, the Montreal Protocol on Substances that Deplete the Ozone Layer was negotiated and signed by 24 countries and by the European Economic Community in September 1987. The Protocol called for the Parties to phase down the use of CFCs, halons and other man-made ODCs. Kofi Annan, Former Secretary General of the United Nations is quoted as saying: "Perhaps the single most successful international agreement to date has been the Montreal Protocol." These two ozone treaties, the Vienna Convention and the Montreal Protocol, have been ratified by 197 states (all United Nations members as well as the Holy See, Niue and the Cook Islands) as well as the European Union, making them the most widely ratified treaties in United Nations history (UNEP 2012).

The Montreal Protocol on Substances that Deplete the Ozone Layer is an international treaty designed to protect the ozone layer by phasing out the production of numerous substances believed to be responsible for ozone depletion. The treaty was opened for signature on September 16, 1987, and entered into force on January 1, 1989. Since then, it has undergone seven revisions, in 1990 (London), 1991 (Nairobi), 1992 (Copenhagen), 1993 (Bangkok), 1995 (Vienna), 1997 (Montreal), and 1999 (Beijing). It is believed that if the international agreement is adhered to, the ozone layer is expected to recover by 2050 (Speth 2004).

The Montreal Protocol is widely considered as the most successful environment protection agreement. The Protocol sets out a mandatory timetable for the phase out of ozone depleting substances. This timetable has been reviewed regularly, with phase out dates accelerated in accordance with scientific understanding and technological advances.

As shown in Table 1, the Montreal Protocol sets binding progressive phase out obligations for developed and developing countries for all the major ozone depleting substances, including CFCs, halons and less damaging transitional chemicals such as HCFCs.

The Multilateral Fund, the first financial mechanism to be created under an international treaty, was created under the Protocol in 1990 to provide financial assistance to developing countries to help them achieve their phase out obligations.

The Montreal Protocol targets 96 chemicals in thousands of applications across more than 240 industrial sectors. The Multilateral Fund has provided more than US \$2.5 billion in financial assistance to developing countries to phase out production and consumption of ozone depleting substances since the Protocol's inception in 1987.

Table 1: Summary of Montreal Protocol Control Measures.

Source: (Commonwealth of Australia 2012)

Ozone Depleting Substances	Developed Countries	Developing Countries
Chlorofluorocarbons (CFCs)	Phased out end of 1995	Total phase out by 2010
Halons	Phased out end of 1993	Total phase out by 2010
CCl ₄ (Carbon tetrachloride)	Phased out end of 1995	Total phase out by 2010
CH ₃ CCl ₃ (Methyl chloroform)	Phased out end of 1995	Total phase out by 2015
Hydrochlorofluorocarbons (HCFCs)	Total phase out by 2020	Total phase out by 2030
Hydrobromofluorocarbons (HBFCs)	Phased out end of 1995	Phased out end of 1995
Methyl bromide (CH ₃ Br)(horticultural uses)	Total phase out by 2005	Total phase out by 2015
Bromochloromethane (CH ₂ BrCl)	Phase out by 2002	Phase out by 2002

The timetable set by the Montreal Protocol applies to bulk consumption of ozone depleting substances. Consumption is defined as the quantities manufactured plus imported, less those quantities exported in any given year. Percentage reductions relate to the designated 'base year' for the substance. The Protocol does not forbid the use of existing or recycled controlled substances beyond the phase out dates.

The Protocol has been further strengthened through five Amendments - London 1990, Copenhagen 1992, Vienna 1995, Montreal 1997 and Beijing 1999 - which have brought forward phase out schedules and added new ozone depleting substances to the list of substances controlled under the Montreal Protocol.

The Montreal Protocol has also produced other significant environmental benefits. Most notably, the phase out of ozone depleting substances is responsible for delaying climate forcing by up to 12 years.

Damage to the Earth's protective ozone layer has sparked unprecedented worldwide concern and action. Since it was agreed internationally in 1987 to phase out ozone depleting substances, 197 countries have ratified the Montreal Protocol. In September 2009, East Timor ratified the Montreal Protocol, making it the first international environmental treaty to achieve complete ratification - a truly remarkable effort that reflects the universal acceptance and success of the agreement (Commonwealth of Australia 2012).

1.4.7 Greenhouse Gases

When energy from the sun reaches the Earth, the planet absorbs some of this energy and radiates the rest back to space as heat (US EPA 2010). The Earth's surface temperature depends on this balance between incoming and outgoing energy. If this energy balance is shifted, the Earth's surface could become noticeably warmer or cooler, leading to a variety of changes in global climate.

A number of natural and man-made mechanisms can affect the global energy balance and force changes in the Earth's climate. Greenhouse gases are one such mechanism. Greenhouse gases in the atmosphere absorb and re-emit some of the outgoing energy radiated from the Earth's surface, causing that heat to be retained in the lower atmosphere. Some greenhouse gases remain in the atmosphere for decades or even centuries, and therefore can affect the Earth's energy balance over a long time period. Factors that influence Earth's energy balance can be quantified in terms of "radiative climate forcing." Positive radiative forcing indicates warming (for example, by increasing incoming energy or decreasing the amount of energy that escapes to space), while negative forcing is associated with cooling.

Greenhouse gases are those that can absorb and emit infrared radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect. In order, the most abundant greenhouse gases in Earth's atmosphere are:

- Water vapor (H₂O)
- Carbon dioxide (CO₂)
- Methane (CH₄)
- Nitrous oxide (N2O)
- Ozone (O₃)

Atmospheric concentrations of greenhouse gases are determined by the balance between sources (emissions of the gas from human activities and natural systems) and sinks (the removal of the gas from the atmosphere by conversion to a different chemical compound). The proportion of an emission remaining in the atmosphere after a specified time is the "Airborne fraction" (AF). More precisely, the annual AF is the ratio of the atmospheric increase in a given year to that year's total emissions. For CO_2 the AF over the last 50 years (1956–2006) has been increasing at 0.25 ± 0.21 percent/year (Canadell et al. 2007).

1.4.8 Global Warming Potential

The global warming potential (GWP) depends on both the efficiency of the molecule as a greenhouse gas and its atmospheric lifetime (US EPA 2010). GWP is measured relative to the same mass of CO₂ and evaluated for a specific timescale. Thus, if a gas has a high (positive) radiative forcing but also a short lifetime, it will have a large GWP on a 20 year scale but a small one on a 100 year scale. Conversely, if a molecule has a longer atmospheric lifetime than CO₂ its GWP will increase with the timescale considered. Carbon dioxide is defined to have a GWP of 1 over all time periods.

For example, methane has an atmospheric lifetime of 12 ± 3 years and a GWP of 72 over 20 years, 25 over 100 years and 7.6 over 500 years. The decrease in GWP at longer times is because methane is degraded to water and CO₂ through chemical reactions in the atmosphere.

1.4.9 Carbon Footprint

The Carbon Trust (2012) defines carbon footprint as the total greenhouse gas emissions caused directly and indirectly by a person, organization, event or product.

A carbon footprint is measured in tons of carbon dioxide equivalent (tCO_{2e}). The carbon dioxide equivalent (CO_{2e}) allows the different greenhouse gases to be compared on a like-for-like basis relative to one unit of CO₂. CO_{2e} is calculated by multiplying the emissions of each of the six greenhouse gases by its 100 year global warming potential (GWP).

A carbon footprint considers all six of the Kyoto Protocol greenhouse gases:

- Carbon dioxide (CO₂)
- Methane (CH₄)
- Nitrous oxide (N2O)
- Hydrofluorocarbons (HFC's)
- Perfluorocarbons (PFC's)
- Sulphur hexafluoride (SF₆).

Wright, Kemp, and Williams (2011) have suggested a more practicable definition of carbon footprint as:

"A measure of the total amount of carbon dioxide (CO₂) and methane (CH₄) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as carbon dioxide equivalent (CO_{2e}) using the relevant 100-year global warming potential (GWP100)."

ASHRAE (2011b) defines carbon dioxide equivalent (CO_{2e}) as a measure used to compare the impact of various greenhouse gases based on their global warming potential (GWP). CO_{2e} approximates the time-integrated warming effect of a unit mass of a given greenhouse gas, relative to that of carbon dioxide (CO₂). GWP is an index for estimating the relative global warming contribution of atmospheric emissions of 1 kg of a particular greenhouse gas compared to emissions of 1 kg of CO₂. The following GWP values are used based on a 100-year time horizon: 1 for CO₂, 23 for methane (CH₄), and 296 for nitrous oxide (N₂O).

1.4.10 Kyoto Protocol

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty that was negotiated at the United Nations Conference on Environment and Development held in Rio de Janeiro from June 3 to 14, 1992. The objective of the treaty was to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The treaty provides a framework for international efforts to stabilize greenhouse gas concentrations in the atmosphere. However, it sets no binding limits on greenhouse gas emissions for individual countries and contains no enforcement mechanisms. These are laid out in the accompanying Kyoto Protocol. The UNFCCC was opened for signature on May 9, 1992, and entered into force on March 21, 1994. As of May 2011, the UNFCCC has 194 parties (United Nations 2013c).

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty that sets binding obligations on industrialized countries to

reduce emissions of greenhouse gases. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005. The detailed rules for the implementation of the Protocol were adopted in Marrakesh, Morocco, in 2001, and are referred to as the "Marrakesh Accords" (United Nations 2013a).

The Kyoto Protocol has 190 parties (all UN members, except Afghanistan, Andorra, Canada, South Sudan and the United States), as well as the European Union are Parties to the Protocol. The United States signed but did not ratify the Protocol and Canada withdrew from it in 2011 (United Nations 2013b).

Recognizing that developed countries are principally responsible for the current high levels of greenhouse gas emissions in the atmosphere as a result of more than 150 years of industrial activity, the Protocol places a heavier burden on developed nations under the principle of "common but differentiated responsibilities."

The Kyoto Protocol's first commitment period started in 2008 and ended in 2012. It established legally binding obligations for developed countries to reduce their emissions of the following greenhouse gases (United Nations 1998):

- Carbon dioxide (C0₂)
- Methane (CH₄)
- Nitrous oxide (N₂0)
- Hydrofluorocarbons (HFC's)
- Perfluorocarbons (PFC's)
- Sulphur hexafluoride (SF₆)

For most Parties, 1990 is the base year for their national greenhouse gas inventory and the calculation of their assigned emission limit. Some Parties have emissions limitations reduced below the base year level, some have limitations at the base year level (i.e., no permitted increase above the base year level), while others have limitations above the base year level. Developing countries do not have binding targets under the Kyoto Protocol, but are still committed under the treaty to reduce their emissions. Under the Protocol, emissions of developing countries are allowed to grow in accordance with their development needs.

International emissions trading allows developed countries to trade their commitments under the Kyoto Protocol. They can trade emissions quotas among themselves, and can also receive credit for financing emissions reductions in developing countries. Developed countries may use emissions trading until 2015 to meet their first-round targets.

During the first commitment period, 37 industrialized countries and the European Community committed to reduce GHG emissions to an average of five percent against 1990 levels (United Nations 2013a).

On 8 December 2012, the "Doha Amendment to the Kyoto Protocol" was adopted in Doha, Qatar. The amendment establishes a second commitment period from 1 January 2013 to 31 December 2020 with new commitments for the industrialized Parties. During this second

commitment period, the industrialized Parties committed to reduce greenhouse gas emissions by at least 18 percent below 1990 levels in the eight-year period from 2013 to 2020; however, the composition of Parties in the second commitment period is different from the first (United Nations 2013a).

The "Doha Amendment to the Kyoto Protocol" also established a revised list of greenhouse gases (GHG) to be reported on by Parties during the second commitment period (United Nations 2012):

- Carbon dioxide (CO₂)
- Methane (CH₄)
- Nitrous oxide (N₂O)
- Hydrofluorocarbons (HFC's)
- Perfluorocarbons (PFC's)
- Sulphur hexafluoride (SF₆)
- Nitrogen trifluoride (NF₃)

The Kyoto Protocol is projected to deliver at least a 5.0 percent reduction in greenhouse gas emissions relative to the baseline by 2010, and a 10.0 percent reduction relative to the baseline by 2020 (United Nations 2011).

1.4.11 Net Zero Energy Buildings (NZEB)

Buildings consume 40 percent of the primary energy and 71 percent of the electrical energy in the US. Driven by economic expansion and population growth that require more and more facility space each year, energy use in the US commercial sector is expected to grow by 1.6 percent per year. This is resulting in an energy impact that is increasing faster than all of the energy conservation measures being taken and retrofits being made to buildings. ASHRAE's vision is that the building community will produce net zero energy buildings (NZEBs) by the year 2030 (ASHRAE 2008).

The concept of NZEBs includes only the energy flows of the building, not the overall sustainability of the building. What qualifies a building as a NZEB can be determined using different metrics.

A **net zero site energy building** produces as much energy as it uses when measured at the site. Applying this definition is useful because verification can be achieved through on-site metering. This tends to encourage energy-efficient designs; however, it does not distinguish between fuel types or account for inefficiencies in the utility grid.

A **net zero source energy building** produces as much energy as it uses compared to the energy content at the energy source on an annual basis. The system boundary is drawn around the building, the transmission system, the power plant, and the energy consumed in getting the fuel source to the power plant. This tends to be a better representation of the total energy impact compared to a site definition. It is challenged, however, by difficulties in acquiring site-to-source conversions and by the limitations of these conversions.

Building owners are typically most interested in **net zero energy cost buildings** because they tend to use energy efficiency and renewable energy as part of their business plan. This definition, like the site NZEB definition, is easy to verify with utility bills. Market forces provide a good balance between fuel types based on fuel availability. Costs also tend to include the impact of the infrastructure. Getting to zero, however, may be difficult or even impossible because of utility rate structures.

The fourth definition, a **net zero energy emissions building**, looks at the emissions that were produced by the energy needs of the building. This is probably a better model for green energy sources; however, like the source NZEB definition, it can be difficult to calculate.

ASHRAE (2008) has adopted the definition that a net zero energy building "is a building that produces as much energy as it uses when measured at the site. On an annual basis, it produces or consumes as much energy from renewable sources as it uses while maintaining an acceptable level of service and functionality. NZEBs can exchange energy with the power grid as long as the net energy balance is zero on an annual basis."

CHAPTER 2: Integrated Whole-Building Design Process

The integrated design process, whereby all of the design variables that affect one another are considered together and resolved in an optimal fashion, is crucial in producing a green building. The integrated design process looks at the entire building as a whole, and emphasis is placed on integrating the different aspects of the building design. It encourages creative interaction between team members and an iterative design process to produce a design that would not otherwise occur to either team member alone (Lewis 2004).

The whole-building design process is a multi-disciplinary strategy that effectively integrates all aspects of site development, building design, construction, and operations and maintenance to minimize resource consumption and environmental impacts. The integrated whole-building design process thinks of all the pieces of a building design as a single system, from the onset of the conceptual design through completion of the commissioning process. An integrated design can save money in energy and operating costs, cut down on expensive repairs over the lifetime of the building, and reduce the building's total environmental impact(LANL 2002).

2.1 Elements of the Integrated Design Process

A critical element of the integrated design process is to promote excellent communications among team members, while conducting the following types of activities:

- Setting goals for performance;
- Getting all team members involved early;
- Conducting design charettes;
- Performing project reviews/peer reviews;
- Establishing working groups on specific issues (e.g., green design); and
- Using building systems commissioning as a project process.

Once designed, the building must be constructed, commissioned and operated in a way that supports the green concepts. But, if it is not first designed with green in mind, it will never achieve the desired results (Lewis 2004).

There needs to be a commitment to achieving a high level of sustainability, which starts with the owner and decision-makers and is communicated to and shared by the entire project team. It is crucial that sustainability be clearly established from the outset as a project value. Once the commitment is made, a set of sustainability goals must be formulated. These goals should be explicit and measurable. They should be performance-based, so they don't constrain the range of ideas and solutions available for the project.

A set of sustainability goals for a refrigerated storage facility would include those stated in Section 1.1.1.:

Minimized refrigeration load

- Robust, reliable, easily maintainable equipment
- High efficiency equipment
- Environmentally friendly refrigerant
- Sustainable construction materials

Once the goals are set, the integrated design process naturally leads to the development of strategies for achieving the goals. These typically are developed in a brainstorming environment, such as a charette or workshop, in which the entire project team participates. All disciplines must be represented as participants in this brainstorming, so the impacts of various systems on each other can be optimized.

A design charrette is a useful tool for communicating the project vision to members of the project team, brainstorming design goals and specific conceptual solutions to meet these goals, and beginning to incorporate sustainability into the planning and execution (LANL 2002). The term "Charrette" is widely used today to refer to an intensive workshop in which various stakeholders and experts are brought together to address a particular design issue.

Once the set of strategy options has been developed, the next step is the analysis step which is essential in determining the right mix of loads and efficiencies to meet those loads for each system (Lewis 2004). Such analysis typically uses life-cycle economics to compare various options, with the goal of selecting the options with the best economic performance. Considerations include payback period, available capital, and relative value of soft benefits (those with non-monetized benefits such as productivity improvements, indoor comfort, etc.) vs. hard benefits (those with monetized benefits such as energy savings, reduced maintenance costs, etc.).

Finally, the integrated design process depends upon a whole range of follow through actions to implement the sustainability strategies effectively and completely. These actions ensure that the project stays focused on delivering the desired environmental performance. These typically include peer reviews, documentation of sustainability measures, commissioning of building systems, post-occupancy evaluations and tuning system performance.

2.2 Integrated Sustainable Design Methodology

The integrated sustainable design process uses a straightforward methodology, shown in Figure 2, which begins by reducing loads to the minimum, then meeting those loads with systems that operate as efficiently as possible, followed by looking for ways to serve those systems from the waste streams of other systems, and finally using renewable resources as the inputs to drive the systems(Lewis 2004).

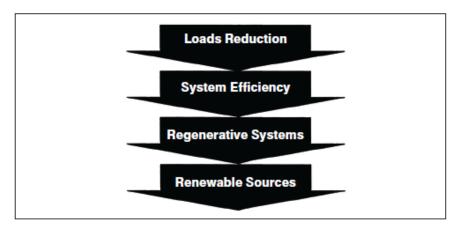


Figure 2: Sustainable Design Methodology.

Source: (Lewis 2004)

2.2.1 Loads Reduction

Reduce Envelope Loads.

- Reduce solar loads
 - -Building orientation
 - -Shading
 - -Glass selection and glass area/location
 - -High-mass building techniques/use of trombe wall designs
- Reduce conduction loads: walls and roofs
- Reduce infiltration loads

Reduce Lighting Loads.

- Lighting design
- Lighting controls

Reduce Power Loads.

- Select energy-efficient equipment
- Design metering for tracking end-use loads

2.2.2 Optimize System Efficiency

- Equipment selection
 - -Equipment right sizing
 - -Systems must be responsive to partial loads
 - -High-efficiency equipment
- New approaches to air distribution

2.2.3 Regenerative Systems

- Using waste energy for useful purposes
 - -Heat rejection from refrigeration system to drive under floor heating systems

- -Heat rejection from refrigeration system to drive service water heating systems
- -Heat rejection from refrigeration system to drive space heating systems for office areas
- Brainstorming the opportunities for using waste energy streams to drive other systems

2.2.4 Renewable Sources

- Using renewable sources to serve loads on-site
 - -Photovoltaic electric
 - -Solar thermal
 - -Wind electric
- Integrate renewable systems into the entire project

2.3 Roles of the Project Team Participants

2.3.1 Owner's Role

- Establish basic value system
- Selection of the team;
- Setting budgets and schedules;
- Maintaining commitment throughout project; and
- Demand/encourage integrated thinking among disciplines

2.3.2 Design Team Role

- Setting sustainability goals:
 - -Energy optimization;
 - -Materials selections;
 - -Systems integration; and
 - -Environmental impact minimization.
- Following the design optimization sequence
- Documenting design intent
- Commissioning the building
- Training the building operators
- Post-occupancy evaluation and feedback

2.3.3 Contractors' Role

- Ensure that all trades understand their job-site sustainability responsibilities
- Monitor and document sustainability activities
- Cooperate with commissioning authorities
- Control adherence with specifications regarding sustainability

2.3.4 Operations Role

Involve building operations personnel in commissioning testing

Train building operators in all sustainability-related systems

2.4 Integrated Design of Sustainable Refrigerated Storage Facilities

Conventional buildings often fail to consider the interrelationship among building siting, design elements, energy and resource constraints, building systems, and building function. Green buildings, through an integrated design approach, take into consideration the effect these factors have on one another. Factors of sustainable structure design that need to be included in an integrated approach to the design, construction, retrofit and operation of green, sustainable, energy efficient, cost-effective refrigerated storage facilities are: building orientation and microclimate; building configuration; insulation type and thickness as well as diminishment of effective R-value over time; economic guidelines; end-user activities; and utilization of thermal mass, cool (high albedo) exteriors and passive solar technologies.

The refrigerated facility must be considered as an integrated whole comprised of the following elements (IARW 1995):

- A superstructure consisting of prefabricated or assembled insulation, providing a controlled environment.
- Doors and other closures to openings in the insulated envelope.
- A floor, insulated as appropriate, and the foundation.

The facility as a whole must withstand the natural forces, including snow, wind, rain and seismic, so that the insulated envelope remains stable and serviceable. Also, the individual elements of the envelope, including the insulation, walls, roofs and support structure, should be able to withstand the rigors of daily use without becoming overstressed or unserviceable (IACSC 1999b).

Small-refrigerated spaces, typically found as insulated envelopes within existing buildings, can be constructed as self-supporting structures from prefabricated panels. The structural capacity of the prefabricated panels determines the size of these self-supporting structures, which are generally 1000 ft³ (28 m³) or less. However, for large super structures, which have refrigerated spaces of several thousand cubic feet or more, additional support must be provided for the insulated envelope.

The performance of the insulated envelope, particularly in relation to the integrity of the joints between prefabricated insulating panels, is highly dependent upon the load and deflection response of the supporting structure. Thus, in the design of these large refrigerated spaces, it is important to consider the insulated envelope and the supporting structure as a unified structure, not two separate structures.

2.4.1 Basic Design Sequence

Procedures for refrigerated storage facility design are complex in nature due to the considerable variety of tasks involved, including planning, financing, site selection, architectural and structural design, refrigeration system design, equipment selection and installation, construction, inspection and maintenance (Becker and Fricke 2005). In addition, considerations of building and safety codes, efficient operation, and cost effectiveness make the design

procedure more complex. The following section gives a brief introduction to the major tasks involved in the design of refrigerated storage facilities.

STEP 1: Specifications

Since the design procedure assumes a particular direction based upon the specifications set by the facility owner and/or the architect/engineer, it is important for the designer to come up with an exact set of specifications that suits all the interests of the owner. Specifications for the overall facility must consider the individual product specifications, storage conditions/arrangements, environmental conditions, and other miscellaneous aspects of the design process.

STEP 2: Site Selection and Preliminary Planning

Based upon the specifications set by the owner and/or the architect/engineer, it is a common practice to prepare a general plan of the facility before a detailed design is done. The following are the considerations that directly influence the general plan of the facility, and in turn, the final design:

- Location and site selection.
- Capacity planning based upon the product specifications, configuration of the facility, storage arrangements, material handling equipment, and the internal layout.

STEP 3: Detailed Design of the Facility

It is the responsibility of the designer to determine the design that meets the requirements of the owner, as closely as possible. For this, a thorough knowledge about the specifications and the details of construction, operation and maintenance of the facility is necessary. This requires a detailed analysis of system practices, including the following:

Construction details:

- Support structures, roofs, floor and walls (civil engineering aspects of design and construction).
- Insulation, vapor retarder, and underfloor heating (thermal aspects of construction and operation).
- Storage and transportation details such as storage arrangements, material handling equipment, dock facilities, etc.

Considerations for the design of the refrigeration system:

- Load calculations.
- System selection practices.

Considerations for safety standards, codes and regulations:

- Life safety.
- Fire safety.
- Food safety.
- Regulatory compliance.

Design procedures and system practices should offer enough flexibility to accommodate changes that may abruptly arise in any phase of the design, for the betterment of the safety standards, efficiency and economic operation of the facility.

CHAPTER 3: Initial Design Specifications

Refrigerated storage facility design, construction and retrofitting involves a variety of tasks, including planning, financing, site selection, architectural and structural design, refrigeration system design, equipment selection and installation, construction, inspection and maintenance. In addition, considerations of building and safety codes, efficient operation, and cost effectiveness make the design procedure more complex (Becker and Fricke 2005).

Perishable food storage requirements, including temperature, humidity and acceptable storage life, vary according to food type. Some products require a curing period before storage. Other products require different storage conditions depending upon their intended use. For certain products, storage life can be significantly extended with special treatments. These various perishable food storage requirements must be considered in the proper design of refrigerated food storage facilities (Becker, Misra, and Fricke 1996a, 1996b).

In order for storage operations to be sustainable and cost-effective, it is necessary to optimally design a refrigerated facility to fit the specific requirements of the particular storage application. These applications include cool storage, where the storage temperature is above 0°C, and freezer storage, where the storage temperature is below 0°C. In addition, a refrigerated storage facility may include ripening rooms, meat thawing rooms, controlled atmosphere storage rooms, food processing facilities, and blast freezers for quickly removing heat from unfrozen food items before storage (Becker and Fricke 2005).

Cost-effective green design and operation of a refrigerated facility requires accurate calculation of the seasonal, hour-by-hour refrigeration load experienced by the facility, including the effects of the diurnal cycle as well as weekends and holidays. Product movement and processing also significantly affect the refrigeration load.

Furthermore, food storage facility design must also comply with applicable codes and standards, including fire codes, ventilation codes, building codes and food safety codes.

Thus, it can be seen that the design, construction, retrofit and operation of refrigerated storage facilities requires knowledge and understanding of a wide range of issues. The complexity of these issues is compounded when considering sustainability, in which a safe and appropriate storage environment is created while simultaneously limiting the impact on the Earth's natural resources.

3.1 Product and Storage Specifications

3.1.1 Product Specifications

The following product specifications should be considered when developing detailed specifications for an intermediate or large refrigerated storage facility (IIR 1993):

 Nature of the product to be produced, handled or stored, including thermal properties and packaging details.

- Product entering temperature.
- Optimal storage conditions, including temperature and relative humidity, for the product.
- Required product outlet temperature.
- Movement of the goods.
 - -mass of products to be chilled or frozen daily.
 - -frequency of entries and exits during the week.
 - -calendar of harvests and dispatches (annually, as in the case of fruits and vegetables).
- Medium-term outlook of production (at least up to five years, if possible)
- Storage temperatures.
- Expected duration of storage, by category or by product type (short-term or long-term).
- Traffic in and out of storage area.
- Material handling methods (hand trucks, pallet trucks, fork-lift trucks, rail conveyor belts, stacker cranes, automated rack system, manual labor, etc.).
- Storage rack type and configuration.
- Inventory management and control.

3.1.2 Product Handling

Bar coding of palletized goods allows forklift drivers the ability to store pallets in the most efficient manner as well as to identify and locate pallets at the moment of dispatching (Duiven and Binard 2002).

3.1.3 Food Safety and Quality

A reduction of 1°C to 2°C (1.8°F to 3.6°F) in the average storage temperature of chilled foods can significantly increase food quality. The weight loss from unwrapped foods will be reduced and bacterial counts will decrease, leading to an increase in safety and shelf life. Also, reduced temperature cycling in frozen food storage rooms will reduce in-package frosting and freezer burn (Foster et al. 2002).

3.1.4 Pallet Temperatures Through the Cold Chain

After monitoring the temperature of pallets of product moving through the cold chain, it was found that there is a very slow change in the temperature at the center of the pallet. For example, it took nearly 20 days for the center of one pallet to fall from the packing temperature of -10° C (14° F) to the storage temperature of -20° C (-4° F). Thus, the inner most products are "unaware" of the transportation phase of the cold chain (BFFF 2009).

3.1.5 RFID Technologies

Temperature monitoring of the cold chain has several social, economic and environmental impacts, including (Estrada-Flores and Tanner 2009):

• Social: Temperature is a prime factor in the cause of food-borne illness.

- Economic: The profitability of the food chain is linked to product mass. Improper refrigeration causes product shrinkage
- Environmental: Food wastage and the resulting wastage of resources used to grow the unused food items due to improper refrigeration.

Radio frequency identification (RFID) technology can be used to improve the performance of the cold chain by (Estrada-Flores and Tanner 2009):

- Providing a means to track the geographical position of packages
- Providing a means to identify items using a unique electronic product code (EPC)
- Providing a means to record and transmit real-time environmental data, including temperature.

3.1.6 Blast Freezing Facilities

While cooling and freezing of food items is not the primary responsibility of a cold store, it is, in some regions, practical for a cold store to be able to cool and/or freeze products which are produced locally. Producers may deliver product to the storage facility at temperatures higher than the required storage temperature. Hence, it may be desirable to install a blast freezer facility to provide contract freezing of products not properly frozen when received. Without a blast freezer, the temperature of the incoming product may not be reduced fast enough to inhibit microbial growth and to reduce the activity of micro-organisms and enzymes, thus leading to product deterioration. This damage may also spread to other stored products if they are warmed by the incoming product (Becker and Fricke 2005).

Blast freezers normally operate at -30°F (-34°C), but may be varied depending upon the storage requirements of the products to be frozen. The incoming product is placed in the blast freezer where it is chilled or frozen to the desired storage temperature, prior to being transferred to the refrigerated storage area.

For the economic operation of the equipment, owners should be encouraged to operate freezers during times when the energy cost is the lowest. In addition, alternative power sources such as natural gas engines or diesel drives may be applicable. The additional investment of a blast freezer may provide a realistic payback, but careful evaluation is required

If the cold storage facility incorporates blast freezing facilities, the blast freezers should not share the same refrigeration circuit as the storage rooms. For example, a blast freezer may require an evaporator temperature of -40°C (-40°F) to quick freeze food products while the storage rooms may require an evaporator temperature of around -25°C (-13°F) to maintain the storage space at -20°C (-4°F). If the blast freezer and storage rooms were connected to the same refrigeration circuit at -40°C (-40°F), the storage room evaporators would be operating approximately 15°C (27°F) lower than required. Approximately 40 percent more energy would be required to operate the storage rooms at the evaporating temperature of -40°C (-40°F) than if they were operating near -25°C (-13°F) (BFFF 2009).

Further energy savings can be achieved by not blast freezing food products to a temperature below that of the cold storage room (BFFF 2009).

In an air-blast cooler or freezer, cold air, supplied from a fan-coil unit, is circulated over the food items, thus removing energy from the product. Typically, air temperatures in the range of -20° F to -40° C (-29° C to -40° C) are used with air velocities ranging from 5 ft s⁻¹ to 20 ft s⁻¹ (1.5 m s⁻¹ to 6 m s⁻¹). The high air velocity reduces the thickness of the boundary layer surrounding the food and thus increases the surface heat transfer coefficient(Becker and Fricke 2005).

Air-blast coolers and freezers are widely used in the industry due to their flexibility and low operating costs. The main advantage of air-blast coolers and freezers is that they are suitable for the cooling or freezing of many different kinds of products.

Air-blast freezers may be categorized as either batch freezers or continuous, inline freezers. Batch freezers, used for small volume freezing, usually consist of crude stationary blast cells and may incorporate simple push-through trolley systems for product loading and unloading. Continuous, inline freezers are used for high volume freezing and include belt freezers, fluidized bed freezers and carton freezers.

Batch Freezers

Stationary Blast Cell

The stationary blast cell is the simplest type of air-blast freezer and it can produce satisfactory results for a majority of food products (ASHRAE 2010a). This freezer basically consists of an insulted enclosure equipped with refrigeration coils and fans that circulate the air in a controlled way over the products.

Products are placed on trays that are then placed into a rack in such a way that an air space is left between every layer of trays. The racks are moved in and out manually. Using this process, nearly any type of food item can be adequately frozen.

Push-Through Trolley Freezer

In the push-through trolley freezer, the racks of the stationary blast cell are fitted with casters or wheels (ASHRAE 2010a). These racks, or trolleys, are usually moved on rails by a pushing mechanism, which can be hydraulically powered. The food products are placed on trays that, in turn, are stacked on the trolleys. The freezer contains one or two rows of trolleys which are pushed forward stepwise along the rails.

Continuous/Inline Freezers

Straight Belt Freezer

In a straight belt freezer, a wire mesh belt is employed in a blast room and provides a continuous product flow (ASHRAE 2010a; Fellows 2000; Dincer 1997). Vertical airflow is used, which forces cold air up through the product layer, thereby creating good contact between the air and the product. Straight belt freezers usually incorporate two belts. The first belt is used to pre-cool or crust freeze the product before transferring it to the final freezing belt, which is designed to accept conditioned products for final freezing. This allows the product to be cooled, dried or crust frozen in a light layer on the first section before being transferred to a more densely loaded second section. The ability to vary conveyor speeds, thus controlling

product depths for gentle handling or fluidization, enables the freezer to handle a wide range of products with only small changes in production capacities.

Spiral Belt Freezer

The spiral belt freezer is the most widely used continuous freezing system in the world (ASHRAE 2010a; Fellows 2000; Dincer 1997). The spiral freezer utilizes a product belt that can be bent laterally and is arranged so that the belt travels in a helical fashion. This allows a very large belt surface to be fit into a minimal floor space, using vertical heights as well as length. The number of tiers or wraps of belt in the spiral can be varied to accommodate different capacities.

In spiral freezers, horizontal airflow is usually supplied by axial fans mounted along one side of the spiral which blow air horizontally across the spiral conveyor. Some freezers incorporate more sophisticated airflow control utilizing extensive baffling and high-pressure fans.

Since the product remains on the belt undisturbed through its freezing process, it is suitable for the freezing of a wide variety of products, including those that require gentle handling.

Fluidized Bed Freezer

Fluidized bed freezers consist of a perforated tray or conveyor belt through which high velocity air (7 ft s⁻¹ to 13 ft s⁻¹ or 2 m s⁻¹ to 4 m s⁻¹) passes vertically upward (ASHRAE 2010a; Fellows 2000; Dincer 1997). The high velocity air lifts the product, producing a fluidized bed of food, which is typically one inch to five inches thick. Fluidization of the product and excellent contact between the food products and the refrigerated air is obtained, thus providing much higher heat transfer rates than those obtained with blast cells or belt freezers. Fluidized bed freezers typically have two stages. After an initial rapid freezing in a shallow bed, which produces an ice glaze on the surface of the food, freezing is completed on a second belt in a bed which is 4 inches to 6 inches (0.10 m to 0.15 m) deep. The shape and size of the food items determine the thickness of the fluidized bed and the air velocity needed for fluidization. The main advantage of this system is that even if the freezer is partially loaded with products, the air distribution will be the same as it is for the full load. Therefore, there are no adverse effects on the airflow around the products from fluctuations in product load.

IQF Freezing

Individual quick freezing (IQF) can be accomplished with fluidized bed and cryogenic freezers. In the IQF technique, each unit of the food product is frozen individually rather than being frozen together in one cluster. The advantage of IQF is that the product can be portioned and poured while still frozen. If the product is block frozen, the entire block must be thawed in order to be poured or portioned.

Carton (Carrier) Freezer

The carton, or carrier, freezer provides an automated technique for freezing medium to large cartons at very high capacities (ASHRAE 2010a). In the top section of the freezer, a row of loaded product carriers is pushed toward the rear of the freezer, while on lower section of the

freezer, the product carriers are returned to the starting point. Elevating mechanisms are located at both ends. A carrier is similar to a bookcase with shelves. When it is indexed in the loading/discharged end of the freezer, the already frozen product is pushed off each shelf one row at a time onto a discharge conveyor. When the carrier is indexed up, this shelf aligns with the loading station, where new products are continuously pushed onto the carrier before it is moved once again to the rear of the freezer.

3.1.7 Cryogenic Facilities

Cryogenics is a deep-freezing process which usually reduces the temperature of an object below -240°F (-151°C) (Kuehn, Ramsey, and Threlkeld 1998; Dincer 1997). Cryogenic freezing has been used in the food industry for many years, evolving through many different processes. Today, recent market demands for "meal solutions" have taken cryogenics into a new dimension. Cryogenic freezing is often a viable alternative for the following scenarios:

- Production on a small scale
- Launching of new products
- Handling overload situations
- Freezing of products which are seasonal in nature

Traditional cryogenic freezing is used for improving frozen product quality, reducing capital expenditures and saving plant space in frozen-food plants. It is used for almost every conceivable food product that is processed today, from shrimp to ice cream.

The major attribute of cryogenic refrigerants is that they are extremely cold. The two practical cryogenic refrigerants are liquid nitrogen, which has a temperature of -320°F (-196°C), and solid carbon dioxide (dry ice), which has a temperature of -110°F (-79°C). Unlike a mechanical freezing unit, in which food is frozen indirectly by the refrigerant via a heat exchanger, the refrigerant in a cryogenic freezing unit has direct contact with the food product. There are several basic types of cryogenic freezers, including tunnels and spirals (Becker and Fricke 2005).

Nitrogen Freezers

A tunnel freezer is the simplest continuous liquid nitrogen freezer (Dincer 1997). It consists of an insulated tunnel with a conveyor belt traveling through it that continuously moves the food product that is being frozen. Liquid nitrogen at -320°F (-196°C) is introduced at the out-feed end of the freezer, directly onto the product, and as liquid nitrogen vaporizes, the cold vapors are circulated toward the in-feed end of the tunnel where they are used for pre-cooling and initial freezing of the products. The "warmed" vapors (typically -50°F or -46°C) are then discharged into the atmosphere. The low temperature of the liquid nitrogen and the nitrogen vapor provides fast freezing. Consumption of liquid nitrogen for most commercial lines ranges from 0.7 to 2.0 pounds of nitrogen per pound of product (0.3 to 0.9 kg of nitrogen per kg of product), depending upon the water content and temperature of the food. This may result in relatively high operating costs, which is the major disadvantage for these freezers.

CO₂ Freezers

In carbon dioxide freezers, boiling (sublimating) carbon dioxide is in direct contact with the foods that are being frozen. Carbon dioxide boils at approximately at -110°F (-79°C), and the system operates similar to a liquid nitrogen freezing system, consuming cryogenic liquid as the food freezes. The basic application of carbon dioxide freezers is for individually quick frozen (IQF) food products.

3.1.8 Specialized Storage And Processing Rooms

As public refrigerated warehouses need to accommodate a variety of products, they often require certain specialized storage rooms (Becker and Fricke 2005). Commonly encountered specialized storage facilities include:

- Controlled atmosphere rooms and minimal air circulation rooms requiring special building designs and mechanical equipment.
- Specialized refrigerated chambers designed to handle a variety of commodities, for which storage temperatures may range from 35°F to 60°F (2°C to 16°C) with humidity control and down to -20°F (-29°C) without humidity control (ASHRAE 2010a).

Controlled Atmosphere Storage

Reduction in the concentration of oxygen and/or increase in carbon dioxide content in a storage atmosphere reduces the rate of respiration of fresh fruits and vegetables and also inhibits microbial and insect growth, thereby reducing the deterioration of the commodities under storage. A combination of refrigeration (chilling) and controlled atmosphere is increasingly important for maintaining high quality in processed and fresh foods for an extended shelf life (Fellows 2000). The term controlled atmosphere (CA) is derived from the fact that the composition of atmospheric gases in contact with the respiring commodities is controlled at precise levels during storage or transportation in order to prolong and extend the storage and market life of fresh fruits or vegetables (Dincer 1997).

Although the benefits of controlled atmosphere storage have been known since the 1920s, when Kidd and West (1927) investigated the respiration of numerous fruits and vegetables in sealed atmospheres, it has only attained wide acceptance since the 1980s. Since then, the range of its applications has grown in volume from fresh fruits and vegetables to fish and meat products, as the ongoing research has already proved that high carbon dioxide concentrations of around 10 percent increases the shelf life of meat products.

In every controlled storage atmosphere, the concentration of non-condensable gases (like oxygen, carbon dioxide and nitrogen) is monitored and constantly controlled, which requires gas tight seals and efficient doors.

Controlled atmosphere storage spaces can be classified, based upon the modes of generation, into product-generated atmospheres and externally generated atmospheres. Product-generated atmospheres are maintained by natural means, in which the room is sufficiently sealed so that the concentration of oxygen is sustained by the respiration of the commodities. Externally generated atmospheres are produced by nitrogen generators or oxygen consumers, along with the assistance of the respiring commodities. For this type of system, hermetically sealed rooms

are necessary even with an external gas generator system. Poor sealing may result in higher operating costs.

Scrubbers are used to control carbon dioxide concentrations in hermetically sealed, controlled atmosphere rooms. Carbon dioxide can be removed by one of the following techniques:

- Passing the room air over dry lime.
- Passing the air through wet caustic solutions.
- Passing the air through water scrubbers, in which carbon dioxide from the room air is absorbed in a water spray. The carbon dioxide is then desorbed from the water by passing outdoor air through the water in a separate compartment.
- Passing the air through a monoethaloamine scrubber, in which the solution is regenerated by a manual process or continuously by automatic equipment.
- Dry absorbents automatically regenerated on a cyclic basis.

For the first two types of scrubbers, the dry lime and wet caustic solutions should be replaced periodically. For additional information on requirements and system practices of controlled atmosphere storage and the scrubbers, refer to the ASHRAE Handbook:, Refrigeration (ASHRAE 2010a), Fellows (2000), and Dincer (2000).

Because of improved product quality and extended shelf life, controlled atmosphere storage is growing in popularity. Thus, it has become advantageous to allocate some space for controlled atmosphere storage rooms in many cold store warehouses (for public storage facilities, in particular). Since controlled atmosphere storage requires high initial investments, it is usually suggested to construct this as a convertible cooler space, whose dividends will be paid off in a reasonable time period.

Temperature, humidity and gas concentration requirements are commodity specific. Refer to the ASHRAE Handbook:, Refrigeration (ASHRAE 2010a), Gomerly (1990), and Dincer (2000) for specific commodity requirements for controlled atmosphere storage. It is important to note that precise control is necessary to achieve good quality.

Specialized Storage and Processing Rooms

Although the vast majority of products coming into any refrigerated storage facility are meant for the cooler/freezer space, there are some products, however, which need special treatment and are handled in sufficient volume in most public cold stores to justify some specialized rooms. Similar to controlled atmosphere storage, it is always recommended to have enough flexibility to accommodate such special situations and, if necessary, to allocate some convertible storage and/or processing rooms, some of which are mentioned in this section.

Modified Atmosphere Packaging (MAP)

Modified atmosphere packaging, also known as gas flushing, is a process in which an atmosphere other than air is placed inside a food package (Fellows 2000). Although the concepts of controlled atmosphere and modified atmosphere seem similar, they should not be confused. Whereas controlled atmosphere refers to controlling the gas concentrations within

the storage room, modified atmosphere involves the use of gases to replace the air within the food package. Modified atmosphere packaging is primarily an efficient packing technique which is used to extend the shelf life of non-respiring products. In order to reduce microbial activity, gases, such as nitrogen, oxygen and carbon dioxide are used to replace air inside the package. To maintain the modified atmosphere, low permeability packing materials are used.

Products in modified atmosphere packaging can be placed in controlled atmosphere storage rooms or regular cooler rooms. Refer to Fellows (2000) for additional information.

Banana Storage and Ripening Rooms

Since ripe bananas deteriorate too rapidly to allow shipping from tropical growing areas to distant markets, bananas are harvested when the fruit is mature but unripe. Harvested bananas are packed into fiberboard cartons and then transported to banana processing facilities via refrigerated ships, trucks and railcars, at an optimum holding temperature of 58°F (14.5°C).

Produce storage facilities which process bananas must include specially designed banana ripening rooms. A typical banana ripening facility consists of a five or more individual ripening rooms. Ethylene gas is introduced into the ripening rooms to initiate ripening. The typical dose of ethylene gas is 1 ft³ per 1000 ft³ of room air space (1 m³ per 1000 m³ of room air space). It is necessary that the ripening rooms be airtight in order for the ethylene gas to be effective. All floor drains must be individually trapped, and all penetrations into the room from refrigerant piping, plumbing lines, etc., must be sealed. Doors must have gaskets all around and a sweep gasket at the floor line.

Direct expansion halocarbon evaporators or propylene glycol fan-coil coolers should be used in banana ripening and storage rooms, since ammonia is harmful to bananas. The cooling units in the ripening rooms should be amply sized to provide an air temperature between 45°F to 65°F (7°C to 18°C) using a refrigerant temperature of not less than 40°F (4.5°C). Also, the relative humidity in the ripening rooms should be held at 85-90 percent (USDA 2004).

Since the design of the banana ripening rooms is critical to the proper ripening of bananas, many major banana processors maintain a technical staff which specialize in the design of banana ripening rooms. Additional design information is available in the ASHRAE Handbook, Refrigeration (2010a).

Meat Thawing Rooms

Refrigerated storage facilities may provide some basic food processing services, such as thawing of frozen meat. Since poor thawing techniques might nullify the high quality achieved by complex and expensive refrigeration practices, it is necessary to have some basic idea about the thawing process. The physical principles of meat thawing are similar to those for freezing, and many of the same points apply. One exception, however, is that thawing generally has to be done less rapidly when compared to freezing, to ensure product quality. Temperature variations in thawing and freezing of meat are shown in Figure 3. Techniques used for thawing include liquid immersion and natural and forced convection of air. Due to the high risk of product contamination and quality degradation, and to comply with procedures such as the

Hazard Analysis and Critical Control Point System (HACCP), care should be taken in the design and maintenance of thawing systems. For thawing procedures and system practices, refer to ASHRAE (2010a), Fellows (2000), and Jeremiah (1996).

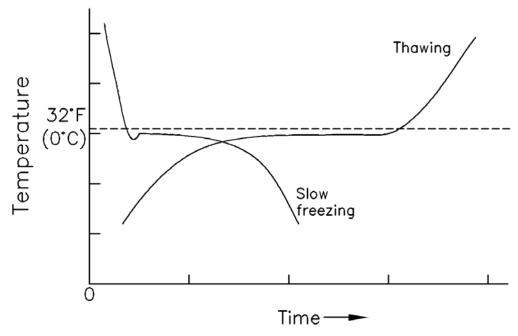


Figure 3: Typical Product Temperature Change during Freezing and Thawing.

Source: (Becker and Fricke 2005)

Tempering Rooms and Special Humidity Rooms:

Since certain canned and packaged products (e.g., milk) are shipped from the cold store in non-refrigerated transport, high ambient temperature and humidity might result in condensation (sweating) on the exterior of the product/packaging. This might damage the appearance as well as the quality of the product. To prevent this damage, a tempering room is required in which products can be warmed prior to shipping, at low humidity conditions.

Although a tempering room needs the same characteristics as a cold storage room, instrumentation and equipment may be more elaborate to facilitate better control of humidity and temperature within the room. In most large refrigerated storage facilities, this room can be as versatile as any other specialized storage facility, and can be readily converted into another specialized storage room upon requirement.

In certain cases, humidity control is also required in addition to temperature control, such as for the storage of candy, film, paper, ice cream, etc. Refer to ASHRAE (2010a), Fellows (2000), and Woolrich and Hallowell (1970) for additional information on specialized storage rooms.

3.2 Facility Specifications

3.2.1 Energy Efficiency

During the construction of new refrigerated storage facilities, the following should be considered (Duiven and Binard 2002):

- Thicker floor, wall, and roof insulation
- Correctly sized compressors
- Speed control for compressors and fans
- Electronic expansion valves
- Adequate pipe dimensions and insulation
- Efficient lighting
- Hot gas defrost
- Computer control systems, monitoring and data processing

3.2.2 Compliance with California Title 24

Section 126 of California's Title 24 gives mandatory requirements for refrigerated warehouses (CEC 2008). According to Title 24, a refrigerated warehouse is defined as a facility with a total cold storage and frozen storage area of 3,000 square feet or larger. Areas within a refrigerated warehouse that are designed solely for the purpose of quick chilling or freezing of food products and with design cooling capacity of greater than 240 Btu/hr·ft² (2 tons per 100 ft²) are excluded.

Insulation

The exterior surfaces of refrigerated warehouses shall be insulated at least to the R-values shown in Table 2.

Table 2: Refrigerated Warehouse Insulation.

Source: (CEC 2008)

Space	Surface	Minimum R-Value (°F·hr·ft²/Btu)
Frozen Storage	Roof/Ceiling	R-36
	Wall	R-36
	Floor	R-36
Cold Storage	Roof/Ceiling	R-28
	Wall	R-28

Underslab Heating

Electric resistance heat shall not be used for the purposes of underslab heating unless it is thermostatically controlled and disabled during the summer on-peak period defined by the local electric utility.

Evaporator Fans

Evaporator fans shall conform to the following, unless the evaporators are served by a single compressor without unloading capability:

- Single phase fan motors of less than 1 hp and less than 460 Volts shall be electronically commutated motors.
- Evaporator fans shall be variable speed and the speed shall be controlled in response to space conditions.

Condensers

For ammonia refrigeration systems, evaporative condensers shall be used. The condensing temperature for evaporative condensers under design conditions shall be less than or equal to:

- The design wet-bulb temperature plus 20°F in locations where the design wet-bulb temperature is less than or equal to 76°F,
- The design wet-bulb temperature plus 19°F in locations where the design wet-bulb temperature is between 76°F and 78°F, or
- The design wet-bulb temperature plus 18°F in locations where the design wet-bulb temperature is greater than or equal to 78°F.

For air-cooled condensers, the condensing temperature under design conditions shall be less than or equal to the design dry-bulb temperature plus 10°F for systems serving frozen storage and shall be less than or equal to the design dry-bulb temperature plus 15°F for systems serving cold storage.

For evaporative condensers, all condenser fans shall be continuously variable speed, and the condensing temperature control system shall control the speed of all condenser fans serving a common condenser loop in unison. The minimum condensing temperature setpoint shall be less than or equal to 70°F.

For air-cooled condensers, all condenser fans shall be continuously variable speed and the condensing temperature or pressure control system shall control the speed of all condenser fans serving a common condenser loop in unison. The minimum condensing temperature setpoint shall be less than or equal to 70°F, or reset in response to ambient dry-bulb temperature or refrigeration system load.

All single phase condenser fan motors less than 1 hp and less than 460 V shall be either permanent split capacitor or electronically commutated motors.

Compressors

Compressors in refrigerated warehouses shall be designed to operate at a minimum condensing temperature of 70°F. In addition, unless the refrigeration plant has more than one dedicated compressor per suction group, the compressor speed of a screw compressor greater than 50 hp shall be controllable in response to the refrigeration load or the input power to the compressor shall be controlled to be less than or equal to 60 percent of full load input power when operated at 50 percent of full refrigeration capacity.

3.2.3 Storage Capacity

The first step towards designing a refrigerated storage facility is to estimate the required storage capacity, which mainly depends upon factors such as traffic levels, nature of goods, expected duration of storage and modes of material handling. In addition, space requirements for loading docks, product handling and logistics must be estimated. Specialists are available to assist in planning, layout and configuration (Becker and Fricke 2005).

Although modern refrigerated storage facilities usually have a volume range of one million to three million cubic feet (28,000 m³ to 85,000 m³) (ASHRAE 2010a), the choice of optimum dimensions for the facility are solely determined by the owner's requirements. This preliminary design decision is usually a rough estimate based on the aforementioned factors and other technical specifications, usually achieved by striking a balance between the capital costs and the operating costs. In developing countries, where cold stores may be smaller, it is essential to plan for future expansion to accommodate the inevitable growth in the quantity of goods requiring refrigerated storage.

An essential step in determining the capacity requirements of the prospective refrigerated storage facility is to acquire data concerning the traffic levels of each of the products and the relative percentages of merchandise for each cooler, freezer and specialized room. It is also essential to have a medium or long-term outlook of production to forecast the storage space requirements with respect to seasonal variations and further growth.

Based upon this data and the estimated capital and operating costs per unit volume of the storage space, optimum dimensions may be determined. Storage capacity is expressed in cubic feet (cubic meters) of refrigerated space available for palletized goods and in linear feet (linear meters) for hanging loads (for instance, beef carcasses). The configuration of the storage facility, i.e., multi-story, single-story or high-rise, is also an essential factor for the determination of storage capacity.

3.2.4 Single- or Multi-Story Configuration

In the recent past, when product handling equipment was not so mechanized, it was often believed that the refrigeration aspect of storage was the most significant contributing factor to the operational costs of a refrigerated storage facility. Hence, storage facility designs which minimized thermal losses were preferred. It was determined that a 'cube-shaped' building would offer the lowest surface area/volume ratio and was considered to be the optimum form. Thus, storage facilities where often constructed in cubical compartments and some with multiple stories(Becker and Fricke 2005).

The multi-storied configuration has the advantage of achieving high storage density on a small amount of land. But with its inherent disadvantages, the multi-story configuration is practically obsolete, since the savings in land and thermal losses do not come close to compensating for the extra costs in construction and product handling. Multi-storied storage levels require heavy-duty support structures and a strong foundation in order to support the heavy loads, both of which are highly expensive. The necessity of moving goods from one level to another requires lifting equipment, and also makes the handling difficult with possible physical bottlenecks

when the product traffic is high. Multi-story cold stores are currently less preferred. They are only warranted in extremely special cases, for example, when a cold store must be built in a crowded urban area, when the location is highly expensive, or in the case of retrofitting an existing dry storage warehouse.

Single-Story Configuration

Most modern refrigerated facilities are of the single-story configuration, with a typical height range of 28 ft to 35 ft (8.5 m to 11 m). The weight of roof/ceiling mounted refrigeration equipment and the self-weight of the walls and the roof are the only loads on the support structure as compared to the weight of the goods on several levels of a multi-storied facility. Thus, span and column height can be increased considerably for a single-story configuration, providing greater storage densities as well as enough space for implementing modern material handling techniques. Small columns on wide centers also permit palletized storage with minimum lost space.

Apart from higher thermal losses due to a less favorable surface area/volume ratio, other disadvantages of a single story storage facility include greater horizontal traffic distances, the necessity of treatment of the floor under freezers to prevent possible ground heaving, and the rather inevitable cost of land. Except for those rare cases where little land is available, the advantages of single-story configuration outweigh its disadvantages, as the initial and operating costs are usually lower than that of a multi-story facility.

High-Rise or Silo-Construction

With the advent of highly mechanized and automated storage and handling techniques, cold-store construction is reaching new heights by stacking goods on pallet racks as high as 80 ft to 100 ft (24 m to 30 m). High-rise construction is preferred in special cases where large storage capacity is required to accommodate high entry and exit flows due to large turnovers. In addition to the excellent work organization facilitated by automatic material handling, significant reductions in thermal losses can be achieved by efficient construction of openings (doors) and even in lighting, as the workers need not enter the refrigerated space. This type of cold store also combines the advantages of multi-story and single-story configurations, as the surface area/volume ratio is greatly improved, thus reducing thermal losses without the disadvantages of the multi-story configuration. However, such facilities need specialized material handling equipment and products must be packaged or palletized in approved ways.

Unlike a medium-height single-story configuration, which is presently considered to be the most effective, high-rise construction remains less popular due to its high initial investment, complicated construction and expensive maintenance.

3.2.5 Cooler/Freezer Space

The designer's most important goal is to create a refrigerated space with the required storage capacity using a continuous insulated envelope and a good vapor retarder. Regardless of the configuration, the floor space of the cold room (cooler/freezer) is occupied either by the storage system (pallet-rack system with the goods in it) or by the traffic areas and the air-side

refrigeration equipment. The total volume of the cooler/freezer space can be divided into three categories(Becker and Fricke 2005):

- Useful storage volume.
- Volume taken up by the traffic lanes.
- Volume required for the air-side refrigeration equipment and for air circulation.

Useful Storage Volume

In addition to the volume occupied by the products themselves, each form of storage arrangement requires some additional space.

The three basic cold storage arrangements used in practice are bulk, solid piling and the pallet-rack system. Bulk storage is rarely used in developed countries but may be used in developing countries. In solid piling, goods are stored in cartons, bales or other packages, and are in direct contact with each other. In a pallet-rack system, goods are stored on standard sized pallets, usually made of wood, which are then stored in racks either static or mobile. The pallets are handled either manually by forklift trucks, or by conveyors in fully automated storage systems.

Pallet-rack storage arrangements are the most widely used systems in modern storage facilities. The volume required for a pallet-rack storage system is composed of:

- The volume occupied by the products themselves or the selected storage unit (individual package, crate or standardized pallet, with or without pallet posts or other specialized equipment).
- Space necessary for accommodating storage elements such as pallet racks.
- Clearance space required for easy access of the individual units.

The shape of the cooler/space depends upon the selected stacking system and the accessibility requirements of the product handling equipment. Consultants and/or vendors specializing in space layout and racking systems should be engaged to optimize the storage space for capacity, installed cost and operating efficiency.

Traffic Lanes

Considering the fact that traffic bottlenecks within the cold room reduce the efficiency of operation, it is essential to have well-planned traffic lanes that allow the handling equipment to reach every corner of the storage space. While the number of traffic lanes depends upon the amount of traffic at peak hours, the width of each lane depends upon the handling equipment and the stacking system in usage. When forklift trucks were first introduced, aisle width was about 12 ft (3.7 m). Currently, aisle width has been considerably reduced to 8.5 ft (2.6 m) for conventional bi-directional trucks, and to 4.3 ft (1.3 m) for tri-directional forklifts (IIR 1993).

Special considerations are required for storage of heavy and compact goods, and also for mobile racks (common in high-rise construction). The choice of racking system and material handling equipment is an important consideration. A compromise between storage capacity and accessibility during handling is required, as better accessibility can only be achieved at the expense of costly refrigerated space.

Placement of Refrigeration Equipment and Air Circulation

Adequate air circulation is required to maintain temperatures within prescribed limits and to avoid temperature stratification. To ensure proper air circulation, evaporators may be ceiling mounted, floor mounted, or located in a penthouse above the refrigerated space. In some cases, there may be partial or full ductwork to provide the necessary air circulation. The number and location of the evaporators is dependent on the room size, configuration, refrigeration load and room temperature requirements. In addition, there should be adequate space for accessibility to the evaporators, piping and operating controls.

3.2.6 Shipping/Receiving Docks

Although most refrigerated storage facilities have separate loading docks for trucks and railroad carriers, loading dock requirements are primarily dictated by the services offered by the facility. Distribution facilities connect to the world through their dock doors and well-designed shipping docks and specialized dock equipment are a prerequisite for efficient management of every storage facility. Shipping docks are meant to provide space for free movement of goods to and from storage, sorting, packing, inspecting, and in some cases, storage of pallet boxes and idle equipment. Refrigerated docks also keep a great deal of moisture from entering the freezer, and a well-designed and insulated dock can also reduce the refrigeration load significantly, which in turn, provides savings in operating costs for a freezer. For cooler facilities, installation of a refrigerated dock reduces the load on the refrigerating units and assures more stable temperatures

The dock should at least be 30 ft (9 m) wide. The choice of width mostly depends upon the traffic levels in the facility. Commercial storage facilities require more dock space than specialized facilities, due to the variety of products to be handled and the higher traffic levels. If the dock is designed for average vehicle height, leveling equipment should be readily available.

Rail dock height and building clearances should be verified by the railroad serving the plant. A rail dock height of 4.5 ft (1.4 m) is typical. The truck dock height should be as high as the average height of the over-the-road trucks servicing the facility. Refrigerated trucks usually require a height of 50 inches (1.3 m). Since refrigerated docks are maintained at temperatures of 35°F to 45°F (2°C to 7°C), and as low as 15°F (-9°C) for ice cream, cushion-closure seals around the truck doorways are necessary to reduce infiltration of outside air. An inflatable or telescopic enclosure can be extended to seal the space between the railcar and the dock. Cost of doors and seals or enclosures, and even refrigeration costs, influence dock size and the number of doors(Becker and Fricke 2005).

3.2.7 Office/Utility Space

Record keeping is a basic requirement for any business and is required for the successful and efficient operation of any industry. For any refrigerated storage facility, there is also an obligation to maintain an exact record of the income and outgo of all the products. Hence, it is inevitable that some space be allocated for functional areas such as an administration office, shipping and/or distribution office (order-picking area), maintenance area, and locker room and

personal welfare facilities. These spaces may be within or adjacent to the facility and all fall under the broad term known as "utility space."

While a superintendent's office and a warehouse records office should be located near the center of operations, a checker's office should be in direct view of the dock and traffic arrangement. If office walls are adjacent to cooler or freezer spaces, these walls should be heated to prevent condensation and mold formation. Building construction should be in complete compliance with the local building codes, and all of these functional areas should be properly ventilated and/or air conditioned(Becker and Fricke 2005).

3.2.8 Machinery and Battery Charging/Fork Lift Storage Rooms

The machinery room should include ample space for refrigeration equipment and maintenance, adequate ventilation, standby capacity for emergency requirements, and adequate segregation from other areas, in addition to all the other requirements in compliance with the building and safety codes. The location of the machine room has great importance. It should be as close to the low temperature evaporators as possible so as to minimize piping distances for the major loads. However, future expansion should also be considered. For this reason, the machinery room is often placed at one end of the building to accommodate future expansion. A maintenance shop and space for parking, charging and servicing warehouse equipment should be located adjacent to the machinery room.

To eliminate inherent safety hazards, electrically operated material handling equipment has nearly replaced combustion-type equipment. The electrically operated equipment requires sound battery recharging facilities to eliminate any potential bottlenecks in handling due to sudden failure of the equipment. Although battery recharging could be done in dock and maintenance areas, construction of a special battery recharging room has become a common practice. The battery recharging room should be located close to the areas where forklift equipment is used. To reduce construction and land costs, the charging room size should be limited.

Battery charging rooms should be maintained at around 70°F (21°C), and should have doors capable of withstanding possible damage due to high temperature gradients. These rooms should also be designed with high roofs. Hydrogen gas detecting equipment must be used in the charging room and proper ventilation is needed to prevent potential hazards due to combustible fumes which result from the charging activity(Becker and Fricke 2005).

3.3 Safety Standards In Refrigerated Storage Facilities

Of all the areas of design and operation of a system, none may be more critical than safety (Becker and Fricke 2005). In the case of refrigerated storage facilities, providing refrigeration capacity with the best possible energy efficiency and being able to meet all the specifications set by the owner/client are important only after safe operation is ensured.

The motivation for safety of any refrigerated facility is to protect people, including employees and the neighboring public affected by the storage facility, and to prevent unexpected events which might cause damage to the stored products. Hence, it is the fundamental responsibility

of the design engineer to observe pertinent safety codes, and to conform to the codes for all facets of the design.

Conformity to codes and standards is also essential in every phase of the long-term life of the facility, including design, construction, installation, operation and maintenance. Hence, standard publications like ANSI/ASHRAE Standard 15-2001, "Safety Standard for Refrigeration Systems" (ASHRAE 2001), and the National Fire Protection Association (NFPA) "Codes, Standards and Recommended Practices" (NFPA 1991) should be observed, starting with the design phase. The design phase should also include provisions for conformity to fire codes such as NFPA 230 (NFPA 1999b), and measures for food and occupant safety, including the Food Code published by the Food and Drug Administration (FDA) (FDA 2001), Recommendations for Chilled Storage of Perishable Products published by the International Institute of Refrigeration (IIR) (IIR 1979), and NFPA 101: Life Safety Code (NFPA 2001). Prior to construction, facility plans and specifications must be approved by the appropriate authority having jurisdiction as well as the fire marshal.

In addition, considering the importance of maintenance in the safe operation of the facility, the designer should incorporate sufficient accessibility for servicing and instrumentation for effective monitoring. The owner/manager of the storage facility should be aware of the risks and safety concerns that exist in a facility, since legal and professional liabilities require that the owner/manager take all possible measures to eliminate or minimize all such risks.

When the facility is designed and constructed in compliance with the specifications given in codes and standards, the task is only partly fulfilled. Numerous opportunities to enhance the safety of the facility as a whole still remain in the areas of placement, construction, installation, operation and maintenance. Regardless of how conscientiously constructed and maintained a storage facility may be, it is still at risk from various sources, explicit or hidden. Considering this, the importance of insurance should never be overlooked.

3.3.1 Fire Safety in Refrigerated Storage Facilities

Despite low temperatures, cold storage warehouses are not immune to fire hazards (Becker and Fricke 2005). Since the inside temperatures of refrigerated storage facilities are of the order of 32°F (0°C) or lower, and the air is dry, these storage environments pose unusual fire prevention and control problems, which may be aggravated when warehouses are located away from water distribution systems. Although fire frequency is relatively low in refrigerated warehouses, the current trend towards larger storage capacities and high-rise rack storage construction increases the fire risk.

Potential Fire Hazards

Although about half the fires that do occur in refrigerated warehouses originate outside the refrigerated areas, there are potential causes of fire in the construction, operation, and maintenance phases of the operational life of refrigerated storage warehouses.

Fire Hazards during Construction

Operations which require the use of heat or open flames have been identified as the major source of fires in refrigerated storage facilities, accounting for at least 34 percent of all the fires, according to a survey on fire hazards in refrigerated warehouses (ASHRAE 2001).

Defective Electrical Installations

Defective electrical equipment has been identified as the source of 30 percent of cold store fires, including embrittlement of insulation at low temperatures, damage to wiring by accidents, chemical attack on cables by acid fumes from battery recharging, and sagging of flexible cables (ASHRAE 2001).

Pallet Storage

The storage of unused pallets may be a potential fire hazard in refrigerated storage facilities. Unused pallets provide a source of dry fuel, their frayed edges are subject to easy ignition, and their open construction provides flue spaces through which fire can grow very hot and spread quickly. The preferred storage location for unused pallets is outside and away from the refrigerated storage facility (50 feet [15 m] or more), or in a detached building

Typically, most pallets are made of wood. However, the durability, reusability, and recyclability of newer plastic pallets have spurred an increase in use of plastic pallets. Their greater flammability requires special attention to fire protection. During a fire, plastic pallets will release approximately twice the amount of heat as compared to wooden pallets. In addition, plastic pallets will burn for longer periods, and may melt and pool, contributing to rapid fire spread.

Hazards due to Solvents and Cleaning Products

Flammable solvents and cleaning agents constitute a potential fire hazard.

Human Factors

Arson and negligence may be potential fire hazards in any structure, including refrigerated storage facilities

Miscellaneous Fire Hazards

Erroneous operation of equipment is also a potential cause of fire in refrigerated storage facilities, particularly during repair and maintenance work. High currents through electrical cables and control equipment, combined with the presence of acid fumes generated during battery charging, make machine rooms, battery charging rooms, and forklift truck parking areas vulnerable to fire.

Fire Prevention

Prevention is the first and the most powerful strategy in reducing fire losses since a good fire prevention program can significantly minimize the risk of fire

Building Construction and Fire Safety

Combustibility, flame spread rate, smoke production, heat release rate, and structural stability should be considered when selecting building construction materials. For information on the behavior of insulating materials and sandwich panels subjected to fire, refer to the International Association of Cold Storage Contractors (IACSC) publication, Design, Construction, Specification and Fire Management of Insulated Envelopes for Temperature Controlled Environments (IACSC 1999b), and the IIR publication, Fire Safety in Cold Stores (IIR 1987). The core of insulating panels should never be exposed, and damaged panels should be repaired as soon as possible.

It is recommended to subdivide the storage facility with partitions and firewalls. It is also recommended to construct certain components, such as the roof and upper walls, with materials that burn quickly. Doing so will aid firefighting operations, since firefighters cannot operate in a burning building until the roof has collapsed or opened up after burning. Annexed buildings must be partitioned from the facility with either firebreak walls or separation distances of the order of 50 ft.

Fire risk may increase during shutdown for repairs or during construction, most commonly from hazardous operations such as welding and cutting. Ensure that only qualified workers carry out such operations, according to the codes and standards of metalworking, such as NFPA 51B: Standard for Fire Prevention During Welding, Cutting and Other Hotwork (NFPA 1999a).

Considering the potential threats due to defective electrical systems and poor electrical installations, special care is recommended in the areas of inspection and maintenance. Refer to ANSI/NFPA 70, National Electrical Code (NFPA 2002c), NFPA National Electrical Code Handbook (NFPA 2002a), ICC International Building Code (ICC 2003a), and ICC International Fire Code (ICC 2003b), for additional information.

Protection against Human Factors

Automatic intruder alarms and surveillance systems should be installed to discourage negligent activities and to deny the potential arsonist access to the premises

Comprehensive routine maintenance is essential to eliminate the risk of fire inside the cold store. Particular attention should be paid to refrigeration system repairs, refrigerant leaks and damaged electrical appliances.

Protection Against Fires

Once a fire breaks out, the only possible way to minimize losses is to contain and extinguish the fire. While detection of fire is the first step in fighting against it, immediate intervention is necessary to suppress it. Failure to incorporate appropriate facilities for detection and intervention can be disastrous for any storage facility.

Fire Detection and Alarm

Detection and alarm systems, and the associated systems of communication, are the means for transferring the information to trigger automatic or manual suppression systems, active fire

confinement systems, and evacuation. The sooner the detection and triggering can occur, the sooner fire mitigation can begin.

Fire detection devices are designed to react to certain elements of the fire, such as heat and light radiation and/or chemical or ionic (smoke) reactions that precede or accompany the onset of a fire. Commonly used fire detectors include ionic, thermal, and optical (smoke and/or flame) types. The selection of detectors should be based upon the types of potential fires expected, the type and quantity of fuel, possible ignition sources, range of ambient conditions, and the value of protected property. The selection and installation of protective devices in refrigerated warehouses are also influenced by the temperature and humidity, the type of storage configuration (single/multi-story/high-rise) and the method of storage.

Detectors located in refrigerated rooms should be fitted with resistance heating and protective devices to avoid frosting. Since it is difficult to detect smoke or gas inside a refrigerated space due to interference from ventilation systems and frost formation, detectors are either fitted with visual signal processors or optical detectors, which are preferred to thermal or chemical/ionic detectors.

Fire alarm systems are crucial for warning occupants of fire, especially in storage areas with low occupancies. Alarm systems should have sounding devices that are distinctive from each other, and these devices should be distributed in such a way that the signal may be heard in every room or area of the building. It is also important to keep the alarm pull stations clear of any storage and they should also be color-coded for easy identification. For additional information refer to the NFPA Fire Protection Handbook (NFPA 1991) and Fire Alarm Signaling Systems (Bukowski and Moore 2003).

Fire Suppression

Automatic sprinkler systems and automatic CO₂ systems are the two most effective forms of fire suppression systems. Water spray protection, high expansion foam systems, portable fire extinguishers, and standpipe and hose systems may also be used to complement mandatory fire suppression systems.

Effectively trained and equipped fire suppression forces are required to completely extinguish a fire. The success of a warehouse fire fighting operation is determined during the development of the warehouse pre-fire plan. A pre-fire plan is a strategic but cooperative approach between the building owner, plant emergency teams, and the public fire departments, to ensure the fire safety of the facility. Input from plant security forces, plant engineering staff, public utility companies, and the insurance carrier are required to develop a successful pre-fire plan. For information on warehouse pre-fire planning and firefighting system practices, refer to the NFPA Fire Protection Handbook (NFPA 1991).

Automatic Sprinkler Systems

Automatic sprinklers are designed to distribute water on a fire in sufficient quantity to control the fire. Automatic sprinklers are thermostatic devices designed to react at predetermined temperatures to release a stream of water and distribute it in specified patterns and quantities

over designated areas. Water is fed to the sprinklers through a system of piping, ordinarily overhead, with the sprinklers placed at intervals along the pipes. Refer to the NFPA Fire Protection Handbook (NFPA 1991), for information on automatic sprinkler systems.

Automatic sprinklers are quite effective for life safety since they serve a dual purpose of warning of the existence of fire as well as applying water to the burning area. Automatic sprinkler protection is recommended for a refrigerated storage warehouse in almost all cases. Room flooding CO₂ or high-expansion foam systems are not acceptable alternatives to automatic sprinklers.

Electrically operated pre-action type sprinkler systems are preferred to dry pipe systems in chill rooms or coolers, while systems with combined features of deluge and dry-pipe sprinkler systems are preferred for freezers and holding rooms. For high-rise rack storage facilities, it is necessary to use in-rack sprinklers to reach spaces that cannot be reached by overhead sprinklers. Automatic sprinkler systems should be designed and installed in accordance with NFPA 13, Installation of Sprinkler Systems (NFPA 2002b). NFPA 230 (NFPA 1999b) is also recommended for reference. For additional information on combination dry pipe deluge systems and other alternatives, refer to the NFPA Fire Protection Handbook (NFPA 1991).

Automatic sprinklers should by no means be considered as the only method of fire protection. Standpipe hose systems, high expansion foam systems, portable fire extinguishers, and manual firefighting operations also play a role in protecting the storage facility, along with passive defenses such as firebreak walls and fire doors. For additional information on these systems, refer to the IIR publication, Fire Safety in Cold Stores (IIR 1987), the NFPA Fire Protection Handbook (NFPA 1991), and Building Construction for the Fire Service by F.L. Brannigan (1992).

Automatic CO₂ Extinction Systems

Automatic CO₂ fire extinction systems are sometimes used as an alternative to automatic sprinkler systems, in which CO₂ is injected into the storage room from a liquid-CO₂ stock, as soon as the fire breaks out. However, it is important to note that CO₂ will react with ammonia to form ammonium carbonate, an irritant to the eyes, skin and respiratory system. In addition, ammonium carbonate may evolve toxic fumes in a fire and may be harmful if inhaled. Thus, CO₂ extinction systems are not used in conjunction with ammonia refrigeration systems.

Carbon dioxide is an effective extinguishing agent primarily due to its ability to reduce the oxygen content in the atmosphere by dilution to a point where the atmosphere will no longer support combustion. The available cooling effect is also helpful, especially where the liquid-CO₂ is directly applied to the burning material. This type of system is universally employed for protecting computer rooms, machine rooms, storage tanks, and also in certain marine applications.

A CO₂ fire extinction installation essentially consists of an automatic detection and alarming system, a triggering device (which may be mechanical, pneumatic or electrical, and a mandatory manual device), and a stock of liquid CO₂ in bottles or in a refrigerated receiver.

All the necessary safety measures should be scrupulously observed to avoid the possible risks of asphyxiation of personnel. Total flooding of an area with CO₂ should not be done until all personnel have been evacuated. The pressure should be lowered inside rooms where CO₂ is flooded.

The main drawback of CO₂ extinction systems is that a large amount of CO₂ is required, on the order of six to 12 pounds per 100 cubic feet (1 or 2 kg per cubic meter) of facility volume. Large refrigerated storage tanks are required to keep the CO₂ in a liquid state and maintain acceptable pressure levels. Furthermore, consideration must be given to the typically slow release rates of a CO₂ system, which greatly affects the fire suppression performance of the system. Thus, in view of all these factors, a CO₂ suppression system should only be used in conjunction with automatic water sprinklers.

Life Safety Considerations

It should be ensured that all firefighting equipment in the refrigerated storage facility is properly maintained and ready for service. The importance of human life over any material property, however precious, can be summed up in the fundamental rule that "in the event of an emergency, no one should risk life or health in order to prevent material damage." It should also be noted that the risks taken by a rescuer to lend help to another person should not be more than that which is absolutely necessary.

Factors affecting life safety in warehouses include the stored commodity (the product, the packing and/or the container), the storage arrangements (characteristics like the height of storage and aisle width), and the characteristics of the storage facility as a whole (fire detection, alarming, automatic suppression equipment, and exterior fire safety access, etc.).

NFPA 101, Life Safety Code (NFPA 2001), addresses the considerations of life safety from fire and similar emergencies and discusses features necessary to minimize danger to life from fire, smoke, fumes, and panic. It also deals with egress design and emergency egress identification. The minimum requirements stated in NFPA 101 should be followed at every stage of the refrigerated storage facility life, including design, construction and operation.

The following is an outline of the essential features for life safety in a storage facility:

- Installation of fire detection and alarm systems as well as sprinkler systems.
- Training of the personnel to combat an emergency.
- Coordinating firefighting plans with the local fire department.
- Installation of fire suppression systems.
- Exit design considerations.
- Exit identification (emergency lighting) and directions for life safety in the event of emergency.
- First-aid facilities.

3.3.2 Food Safety in Refrigerated Storage Facilities

One of the most significant applications of refrigeration is to retard microbial, physiological, and chemical changes in foods and thereby extend the shelf-life of foodstuffs (Becker and Fricke 2005). However, a constant battle is waged against food contamination and the resulting foodborne diseases. Improperly sanitized equipment and unstable storage temperatures are the two most important causes of food-borne illness.

Even at temperatures near the freezing point, food may deteriorate through the growth of microorganisms, through changes caused by enzymes or through chemical reactions. Holding foods at low temperatures cannot completely eliminate deterioration, but merely reduces the rate at which this deterioration takes place. Chemical and biological characteristics of foods such as nutrients, inhibitors, pH, water activity, biological structures, and the presence of pathogens (disease causing microorganisms) are factors influencing microbial growth that are intrinsic to the food item. On the other hand, extrinsic factors are those that are the characteristics of the storage environment, which include temperature, relative humidity, and oxygen levels in the storage environment. Control of these extrinsic factors, which can be achieved by refrigeration and ventilation systems, greatly influences the growth and activity of microorganisms.

Design for Microbial Growth Control

Microorganisms can be controlled by one of the following three mechanisms:

- Prevention of contamination.
- Inhibiting microbial growth.
- Destruction of the microorganisms.

Prevention of Contamination

Refrigeration prolongs the shelf-life of stored commodities by reducing microbial enzyme activity and toxin production, but in most cases, it will not reverse a pre-developed situation. Prevention of contamination is the best method to avoid damage to the stored commodity. To minimize the possibilities of contamination, equipment and facilities should be designed in strict compliance with the standards and practices of food safety as discussed in the FDA Food Code (FDA 2001).

Inhibiting Microbial Growth

Inhibiting microbial growth through temperature and humidity control is the primary means to achieve food safety in refrigerated warehouses. Refer to the ASHRAE Handbook of Refrigeration (ASHRAE 2010a) for commodity specific recommendations on temperature and humidity for long-term refrigerated storage. Refer also to the following two publications by the International Institute of Refrigeration (IIR): Recommendations for the Processing and Handling of Frozen Foods (IIR 1986), and Recommendations for Chilled Storage of Perishable Products (IIR 1979).

Since a variation of 2°F to 3°F (1°C to 2°C) in product temperature above or below the desired temperature is too large in most cases, the temperature in a cold storage room must be accurately maintained to achieve product quality. Also, it is recommended that the relative humidity in the refrigerated storage space be maintained within 1 to 2 percent of the desired level for fresh produce while a tolerance of 3 to 5 percent is acceptable for frozen product. A record of temperatures (both product and air temperatures) and relative humidity is necessary to determine the performance of the storage facility. Hence, good quality measuring and recording devices should be installed, maintained and periodically calibrated.

Proper air circulation is required to maintain a uniform temperature within a refrigerated storage facility. Air movement is necessary to remove respiratory heat and heat infiltration through walls, roofs and doorways. Since the internal configuration of the storage space and the stacking arrangement are the most influential factors affecting air distribution, the air distribution system should be designed in conjunction with the internal configuration of the refrigerated storage facility and the stacking arrangement.

When product is delivered to the storage facility at a temperature measurably greater than the storage temperature, it is recommended that the product be rapidly pre-cooled to the storage temperature in a separate pre-cooling room. The pre-cooler should have a higher air circulation rate and a greater refrigeration capacity to rapidly remove field heat from freshly harvested commodities, residual heat from processing operations, and/or heat gained during transport. Since excessive air movement can increase moisture loss from the product, resulting in the loss of both mass and quality, high air velocities are undesirable after pre-cooling, unless high humidity is maintained.

Humidity control is one of the most effective means of inhibiting microbial growth. Condensation on ceilings and chilled pipes supports microbial growth and may drip onto product, causing contamination. Efforts to prevent condensation are essential to prevent contamination. Condensation drip pans should be plumbed directly to drain completely, while providing easy access for periodical cleaning. In addition, increased airflow may also be useful in removing residual moisture. Since sanitation procedures use much water and leave the surfaces wet, adequate dehumidification should be provided for removal of moisture during and after sanitation.

Destruction of Microorganisms

A constant low temperature within the refrigerated storage facility is important for both the destruction of microorganisms and the maintenance of product quality. Not only is microbial growth reduced at low temperatures, but better product quality is maintained when storage temperatures remain constant. Fluctuating storage temperatures should be avoided since they promote the growth of ice crystals within the food, thus causing damage to the food.

Role of HACCP in Food Safety

Most private refrigerated storage facilities include certain specialized food processing rooms, and other related operations which require knowledge of the mandatory safety measures for

food processing. Food manufacturers and regulators have adopted the Hazard Analysis and Critical Control Point System (HACCP) to ensure safety of food products. HACCP was developed nearly 30 years ago for the space program and is now accepted by food manufacturers and regulators. HACCP is a management system in which food safety is addressed through the analysis and control of biological, chemical, and physical hazards from raw material production, procurement and handling, to manufacturing, distribution and consumption of the finished product. It is a preventive system that builds safety control features directly into the food processing methodology, and it is effective in managing physical, chemical, as well as biological hazards.

HACCP is a systematic approach to the identification, evaluation, and control of hazards to food safety based upon the following seven principles developed by the National Advisory Committee on Microbiological Criteria for Foods (NACMCF):

- Principle 1: Conduct a hazard analysis.
- Principle 2: Determine the critical control points (CCPs).
- Principle 3: Establish critical limits.
- Principle 4: Establish monitoring procedures.
- Principle 5: Establish corrective actions.
- Principle 6: Establish verification procedures.
- Principle 7: Establish record-keeping and documentation procedures.

For additional information on HACCP procedures, practices and implementation, refer to the FDA, Food Code (FDA 2001).

CHAPTER 4: Facility Design

Conventional buildings often fail to consider the interrelationship among building siting, design elements, energy and resource constraints, building systems, and building function. Green buildings, through an integrated design approach, take into consideration the effect these factors have on one another. Factors of sustainable structure design that need to be included in an integrated approach to the design, construction, retrofit and operation of green, sustainable, energy efficient, cost-effective refrigerated storage facilities are: building orientation and microclimate; building configuration; insulation type and thickness as well as diminishment of effective R-value over time; economic guidelines; end-user activities; and utilization of thermal mass, cool (high albedo) exteriors and passive solar technologies.

This section will begin with a description of the initial planning stages of design for a refrigerated storage facility, including general layout and siting, with emphasis on utilizing the available local natural environment so as to benefit the facility while reducing the facility's impact on the environment.

This section focuses on the specific aspects of facility structure design, including walls, roofs, floors, and doors. Issues such as selecting environmentally preferable building materials, optimizing insulation thickness, installation of the vapor retarder, reducing infiltration and analyzing traffic flow to optimize material handling systems is covered.

4.1 Facility Siting

Where buildings are situated on a site can have a huge impact on the overall greenness of a facility. Try to concentrate development impacts while retaining as much undeveloped open space as possible. Locate buildings and roadways to minimize site disturbance, particularly where significant wetlands and wildlife habitat (including wildlife corridors) are present. Keeping buildings and infrastructure on an area of the site close to public highways and with easy access to utilities will reduce material use, minimize new impervious surfaces, and permit as much open space as possible to be retained (DOE 2001).

4.1.1 Location and Ecosystem

Location is one of the most important factors in the overall success of both private and public refrigerated storage facilities (Becker and Fricke 2005). Private storage facilities are usually constructed in proximity to the owners' other operations. Public storage facilities, however, should be in areas of large production/consumption, and/or a convenient transit storage point, or a combination of these, in order to develop a good average occupancy and serve the customer's interest.

The most important factors to be considered in selecting a site for a facility are:

- Convenience for production, shipping and distribution.
- Easy access to main highway truck routes and local routes, with minimum congestion.

- Easy access to good railroad services, if desired.
- Easy access for employee commute.
- Location with reasonable land cost.
- Ample land for trucks and employee parking, truck movement, and plant utility space with room for future expansion.
- Adequate infrastructure available: sewer, water, gas, electric, communications, etc.
- Provisions for surface waste and sanitary water disposal.
- Location away from residential areas where the sights and sounds resulting from the operation of a refrigerated storage facility would not be objectionable.
- Favorable, stable under-soil bearing conditions and good storm and surface drainage.
- Constructed sufficiently above the local water table to minimize moisture infiltration and cold room floor heaving.
- Local codes and restrictions.
- Minimal tax and insurance burdens.
- Consideration for plant security, fire protection and zoning limitation.
- Provision for future expansion, if required.
- Restrictions due to regulatory acts and codes (e.g., for classified industrial buildings, city zoning texts, environmental impact studies, etc.).
- Requirements for emergency such as fire services.

The site location should be generally free of airborne particles such as dust, road fumes, sewage odors, industrial fumes (chemical, paint, metal waste, etc.), farm wastes (manure, dust from plowing), etc., which could contaminate the fresh air intake and/or refrigeration coils (evaporators and/or condensers).

Sites located away from congested areas outside city limits are often preferred as the increased trucking distance is compensated for by better plant layout possibilities, and sufficient space for future expansion, as well as certain other advantages, such as local tax considerations, that would boost the economic operation of the facility.

After gaining enough insight into the technical specifications, a site plan is usually prepared, which should be in compliance with the interests of the owner. The site plan will serve as a general outline and a foundation for the complicated design procedure that follows. This general plan should be prepared under the supervision of the project manager and incorporate enough flexibility at every stage of the planning procedure that the overall configuration of the facility will best suit the interests of the owner.

4.1.2 Microclimate

Climatic conditions that should be considered include maximum and minimum outside temperature for the hottest and coldest periods of the year, average outside annual temperature (also monthly and bimonthly averages, if required), relative humidity (extreme monthly or

seasonal values), average annual rainfall, prevailing winds and average annual snowfall. For more information refer to ASHRAE climate/weather data (ASHRAE 2009).

Thoughtful placement of the building on the site promotes energy conservation by taking advantage of natural site features such as breezes, sunlight, shade, and topography. Good site planning minimizes site-clearing (saving money), and preservation of existing vegetation may provide a low maintenance landscape that avoids supplemental irrigation and fertilizer. Mature stands of native vegetation often provide the desired energy-conserving shade and wind control that would otherwise require years to develop from expensive new planting (DOE 2001).

4.1.3 Orientation

Site plans that consider orientation in the placement of buildings provide abundant opportunities to benefit from natural systems. Orientation of a cold store's refrigerated dock with respect to the prevailing winds has a significant effect upon infiltration during the loading and unloading operation. Often, refrigerated storage facilities are oriented on the property to present an aesthetically pleasing façade from the street and/or provide easy access to the dock by the refrigerated trucks with little or no regard to the microclimate. However, by orienting the refrigerated dock so that it does not face into the prevailing wind will greatly reduce infiltration and thereby reduce the refrigeration load and the defrost frequency, ultimately reducing energy costs.

Rectangular buildings should be oriented with the long axis running east-west. In this configuration, east and west walls receive less direct sun in summer, so unwanted heat gain is reduced. South-facing walls achieve the most solar gain during the winter, while the least in the summer. East and west vertical orientations and horizontal orientation all result in more heat in the summer than winter.

Site topography needs to be considered too. Slopes to the south allow for plenty of solar access, while north facing slopes will provide good shading opportunities.

Driveways and parking lots should be located on the east or north side of buildings in southern climates. This reduces heat buildup during hot afternoons. Existing or newly planted shade trees can cool these surfaces.

4.1.4 Shade Trees

Proximity of trees to buildings should take into account growth rate, life span, and ultimate canopy shape (DOE 2001). Evergreen trees may provide shade and block cold winter winds, but on the south side deciduous trees are preferred because they lose their leaves and admit more sun in the winter. When existing tree plantings are too dense, selective thinning and lifting of the canopy may improve air movement, enhance ground-level vistas, and allow remaining trees better growth potential.

Special care should be used in construction near trees. Important plant areas and trees to be retained should be effectively barricaded to prevent damage. Tunneling should be used for utility lines instead of trenching near trees. Roots and limbs should be cut cleanly. Trees

should be watered well before major cutting to invigorate the tree. When major roots are cut, light canopy pruning will reduce transpiration stresses.

Shade and air movement modification depend on height, growth rate, seasonal leaf persistence, canopy shape and density, seasonal solar angles, wind velocity, proximity, and height of structure. Generally, trunks of trees that grow to less than 40 feet (12 m) tall can be as close as 10 feet (3 m) from walls. Trees that grow over 40 feet (12 m) should be kept further from walls. To allow air movement, lower branches near buildings should be removed as the tree grows.

Use trees and other plantings to reduce cooling costs. Carefully situated and selected trees, shrubs, annuals, and vines can provide access to the winter sun (for passive solar heating and day-lighting) while shading the building from hot summer sun. Tall deciduous trees with few low branches are effective near south-facing windows. Lower vegetation, such as tall annuals and deciduous vines, is appropriate for west- and east-facing windows, though trees can also be appropriate.

Arbors and trellises over walkways and outdoor activity areas can provide attractive, functional shade. Plants also create cooler temperatures by evaporating water from their leaves and, depending on humidity, can lower outdoor air temperature several degrees. Shrubs can influence airflow. Evergreen shrubs planted closely together and somewhat near a building wall can create a "dead-air" space around a building that reduces heat loss in winter. In summer, these same shrubs can provide cooling by evaporation and by shading the walls from early-morning and late-afternoon sun. Maintain a 2-foot (0.6 m) clear-zone between shrubs and the building walls to allow for maintenance access and to reduce mildew on exterior surfaces and insect access to the building.

4.1.5 Stormwater Management

Stormwater is precipitation that does not soak into the ground or evaporate but flows along the surface of the ground as runoff (DOE 2001). Conventional practice for stormwater management, concentrating runoff and carrying it offsite as quickly as possible through storm sewers, causes various environmental problems, including erosion and downstream flooding, pollution loading of surface waters, and reduced groundwater recharge.

Responsible management of stormwater involves a combination of strategies to reduce the amount of runoff generated, to reduce the amount of pollutants that are transported in the runoff, and to remove pollutants from that runoff. Generally, the most important management strategy for stormwater is to provide for infiltration into the ground as close as possible to where the precipitation falls. Consider opportunities for improving stormwater management practices when any of the following occur: landscape redesign or replanting, re-grading of the site in any way, excavation of utilities, reroofing of buildings, street and sidewalk modifications, and replacement, addition, or resurfacing of any paved areas. Strategies for improving stormwater management can also improve wildlife habitat on a site, improve water quality in the region, and help to recharge underground aquifers.

Stormwater runoff and erosion during construction are of particular concern and generally necessitate actions well beyond practices for stormwater management once the facility is

developed. Consider both long-term storm-water management issues and short-term erosion impacts during construction. Avoid very steep slopes and those with unstable soils. Avoid changes to topography, vegetation, and landforms. Most disturbances to a site, including grading (which compacts soils) and removal or disturbance of vegetation, will increase stormwater flows by reducing the ability of soils to infiltrate rainwater. Preserving original topography is generally recommended, though re-contouring land, if planned and done carefully, can also improve infiltration in some cases.

Ensure that heavy equipment is reliable and well maintained and does not leak hydraulic fluid, oil, or fuel. Erect temporary barriers such as straw-bale silt fences to capture sediment in runoff. Re-grade and replant disturbed areas (preferably with native plants) as soon as possible.

4.1.6 Permeable Pavement and Green Roofs

Minimize impervious paved surfaces. Minimize the size of parking lots and the width of roadways. Use porous paving, such as porous asphalt, porous concrete, modular block pavers, and specialized grass-paving systems. Separate impervious surfaces with turf, gravel, or vegetation to increase infiltration. Avoid curbs where possible as they increase the concentration of pollutants. When there are no curbs, rainwater runs off driveways, sidewalks, and roads and goes directly into the ground.

Consider green roofs as a stormwater management strategy. By capturing and absorbing rainfall, green (vegetated) roofs function like stormwater detention basins by slowing down the flow of runoff.

4.2 Envelope Design

The insulated envelope provides two main functions: 1) Reduction of refrigeration load, and 2) Prevention of moisture infiltration and condensation. Both heat and moisture penetration will be addressed in this section. In addition, general discussions about the types of insulation available, optimum thickness of the insulation, and basic insulating technique are included. Furthermore, the types of vapor retarders and their ratings as well as general guidelines for their installation are covered.

4.2.1 Insulation

Insulation plays an integral role in reducing the refrigeration load of cold stores, thus minimizing the operational cost of the facility (Becker and Fricke 2005). Insulation also provides adequate support to wall facing materials to resist permanent deformation due to low magnitude impacts; furthermore it provides sufficient fire resisting properties and, in conjunction with the other materials in the wall, provides a structural member capable of withstanding applied loads (IACSC 1999b). The selection of the proper insulating material should be based on temperature requirements, economics, finish, sanitation and fire protection.

Types of Insulation

Insulation used in refrigerated storage facilities may be classified into five types (ASHRAE 2010a):

- Rigid insulation.
- Panel insulation.
- Foam-in-place insulation.
- Precast concrete insulation panels.
- Other insulation materials.

Rigid Insulation

Rigid insulation used in refrigerated facilities is usually made from one of the following four polymeric foam materials:

- Polystyrene: Expanded Polystyrene (EPS) and/or Extruded Polystyrene (XPS)
- Polyisocyanurate (PIR)
- Polyurethane (PUR)
- Phenolic

These materials have proven to function adequately when used with a properly installed vapor retarder and when finished with materials which provide a sanitary surface as well as fire protection.

Expanded polystyrene insulation is created from small polystyrene beads which contain pentane gas. The beads are exposed to heat, thus expanding the pentane gas. The cells within the expanded beads are eventually filled with air during an aging process. Then, the expanded beads are placed into a mold to produce expanded polystyrene sheets. Expanded polystyrene insulation is an efficient thermal insulating material.

Extruded polystyrene is produced in a continuous extrusion process where a blowing agent is added to molten polystyrene to produce a rigid closed-cell material. Extruded polystyrene has good resistance to moisture absorption and has good mechanical properties.

Polyurethane foam is produced by mixing liquid polyether polyol and liquid polyfunctional isocyanate along with several additives. Polyurethane foam has a low thermal conductivity, making it an excellent insulator for applications where panel thickness is a concern.

Polyisocyanurate foam is made in a similar fashion as that of polyurethane foam, however, the ratio of the constituents and the additives are different, resulting in a polymer which has high temperature resistance and relatively low combustibility.

Phenolic foam is produced from phenol formaldehyde and contains a plasticizer, a surfactant, a blowing agent and an acidic catalyst. Phenolic foam has very low flame spread with negligible smoke emission and a very low level of toxic gas emission. However, due to the acidic nature of phenolic foam, corrosion of structural support members is possible.

Panel Insulation

Prefabricated insulated panels are composed of two outer metal sheets surrounding an insulation core. The insulation core of these panels is generally made from either polystyrene or urethane, since these materials lend themselves favorably to panel construction. The outer skin

of the insulated panel (the warm side of the panel) also acts as an effective vapor retarder. The panels are generally attached to the structural members of the facility or against a wall. However, internal walls may be free standing.

The advantages of using prefabricated insulated panels are as follows:

- Prefabricated insulated panels are economical.
- Prefabricated insulated panels are easily repaired, due to their modular design.
- The capacity of the cold store can be easily expanded.
- Prefabricated insulated panels are readily demountable and reusable.

Foam-in-Place Insulation

Foam-in-place insulation requires special equipment for its installation. A portable blending machine and a spray or frothing nozzle are used to feed the insulation into wall, floor, or ceiling cavities, resulting in a monolithic insulation construction without any joints. However, foam-in-place insulation has limited vapor resistance and requires a clean substrate for adherence. Foam-in-place insulation also needs a covering such as fiber reinforced plastic (FRP) where sanitation and wash-down are required.

Precast Concrete Insulation Panels

The use of precast concrete insulation panels is a specialized construction technique and is only successful when used in conjunction with a properly installed vapor retarder. When using precast concrete insulation panels, continuity of the vapor retarder is essential for a successful installation.

In addition, when using precast concrete panels, the designer must consider the effects of the panel mass when sizing refrigeration equipment. Since the high mass of the concrete panels lowers peak loads, less refrigeration may be required as compared to light-weight buildings.

Other Insulation Materials

Other types of insulation, which are less often used, but are worth mentioning include:

- Mineral rock fiber
- Cellular glass
- Glass fiber

The use of wood-based insulation materials should be avoided. Wood chips, cork, straw and other similar materials have been used as insulating materials with generally poor results. These materials have been replaced universally by synthetic materials which are either less affected by or not subject to the problems of organic materials (i.e., fire, moisture, insects, mold, breakdown, etc.).

Mineral Rock Fiber

Mineral rock fiber insulation includes glasswool, slagwool and rockwool. These types of materials have been used as insulators for a long time and are still being used today. However,

one has to be careful when using these materials, as there is a great diversity of grades. Some of these insulating materials have been known to contain small amounts of asbestos.

Cellular Glass/Glass Fiber

Cellular glass has a very low water vapor permeability and high compressive strength. It is used primarily for floors and under columns which support heavy loads. Glass fiber, on the other hand, is a lightweight material that cannot support weight and has a high water vapor permeability. However, it has a low first cost, while cellular glass is much more expensive. Glass fiber performs well with an appropriate vapor retarder properly applied.

A summary of the properties of some insulating materials is given in Table 3. Note that some insulation R-values degrade over time, and age-rated R-values must be used in load calculations. Age-rated R-values are be determined experimentally and should be available from the insulation manufacturer.

Table 3: Properties of Various Insulating Materials.

Source: (Stoecker 1998)

Material	Density, lb ft ⁻³ (kg m ⁻³)	R-Value per inch (2.54 cm), hr ft ² °F Btu ⁻¹ (m ² K W ⁻¹)	Relative Water- Vapor Permeability	Compressive Strength, psi (kPa)	Relative Cost
Molded Polystyrene	1.0 (16)	4 (0.70)	Low	12-17 (83-117)	Low
Extruded Polystyrene	5.4 (86)	5.4 (0.95)	Low	8-40 (55-276)	Medium
Polyurethane*	2.0 (32)	6.5 (1.1)	Medium	25 (172)	Medium
Polyisocyanurate*	2.0 (32)	6.6 (1.2)	Medium	20-30 (138-207)	Medium
Cellular Glass	8.5 (136)	3.0 (0.53)	0	100 (689)	High
Glass Fiber	2.3 (37)	4.2 (0.74)	High	N/A	Low

*Blowing agent dependent.

Insulation Thickness

It is estimated that approximately one third of all cold storage heat gain is due to heat transmission through the insulated envelope. However, insulation thickness cannot be

increased at will, as insulation cost should be balanced against refrigeration energy cost. Table 4 shows the recommended thermal resistance, or *R*-value, of insulation for various refrigerated storage rooms. Also, ASHRAE (2009) provides detailed guidelines for the calculation of *R*-values for various wall sections, including the effects of thermal bridges. However, to obtain exact *R*-values, the insulation manufacturer should be consulted.

Table 4: ASHRAE Recommended R-Values of Insulation.

Source: (ASHRAE 2010a)

	Thermal Resistance, R, °F ft² h Btu⁻¹ (m² K W⁻¹)			
Type of Facility	Temperature Range, °F (°C)	Floors	Walls/ Suspended Ceilings	Roofs
Cooler	40 to 50	Perimeter	25	30 to 35
	(4 to 10)	Insulation Only	(4.4)	(5.3 to 6.2)
Chill Cooler	25 to 35	20	24 to 32	35 to 40
	(-4 to 2)	(3.5)	(4.2 to 5.6)	(6.2 to 7.0)
Holding Freezer	-10 to -20	27 to 32	35 to 40	45 to 50
	(-23 to -29)	(4.8 to 5.6)	(6.2 to 7.0)	(7.9 to 8.8)
Blast Freezer	-40 to -50	30 to 40	45 to 50	50 to 60
	(-40 to -46)	(5.3 to 7.0)	(7.9 to 8.8)	(8.8 to 10.6)

The International Association of Refrigerated Warehouses (IARW) lists the following additional considerations and precautions with regard to insulation (IARW 1995):

- Perimeter insulation may be necessary in the floor between a refrigerated dock and adjacent unrefrigerated areas to prevent condensation on floor of the adjacent unrefrigerated areas.
- In a cooler room where the temperature is always above freezing and the presence of moisture is negligible, perimeter insulation in the floor is sufficient.
- Regardless of the insulation thickness, freezer floors must always include a well-designed underfloor heating system.
- Without a well-designed vapor retarder, no insulation system is complete. Special attention must always be given to critical areas such as junctures (i.e, wall to wall, wall to ceiling, wall to floor, etc). The success of a cold store will largely depend on the effectiveness of the vapor retarder.
- Always consider blast freezers and freezing tunnels separately. In these areas, the heat loss through the insulation is always less than the product load. Therefore, it is difficult to justify increasing the insulation thickness for blast freezers and freezing tunnels, beyond that required to retard condensation on their external surfaces.

Insulation Techniques

Two basic construction techniques are generally used for refrigerated facilities:

- External Frame, Internal Insulation.
- Internal Frame, External Insulation.

Figure 4 illustrates both of these construction methods.

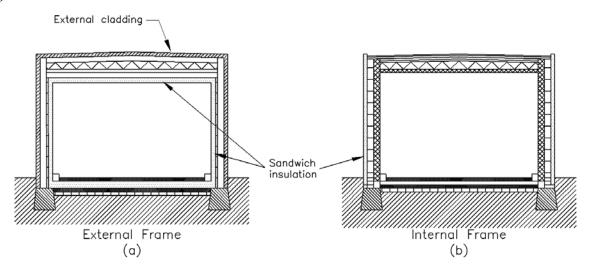


Figure 4: Illustrations of External and Internal Framing.

Source: (Becker and Fricke 2005)

External Frame, Internal Insulation

The supporting structure in the external frame technique is located entirely on the outside of the cold space and the insulation is applied within this supporting structure. The ceiling in this type of construction is independent of the roof and is supported by trusses. It must be made of a light weight material and also be leak-tight. The walls can be made leak-tight by either installing external metal, concrete or masonry cladding covers.

The external frame, internal insulation design enables cold stores to be built without any internal structural elements, which simplifies the storage and handling processes. In addition, this design limits the influence of climatic conditions on the insulating materials. This is especially important for the ceiling, which will not be affected by direct sunlight, thus reducing the possibility of thermal shock. However, the lack of internal structural elements limits the size of this type of facility and the supporting frame is prone to warpage due to variations in the external environmental conditions. Larger structures require thermally isolated internal framing.

Internal Frame, External Insulation

The entire support structure for the internal frame, external insulation design is located within the cold store and the insulation is installed externally. The insulation panels used in this construction technique must provide adequate resistance to heat and moisture transfer and also act as a barrier to weather conditions. The insulation panels must withstand natural forces such as wind, snow and ice, and pass these loads onto the supporting structure.

The materials used for the support structure have to be carefully selected to withstand the cold conditions within the storage facility. (A discussion of sustainable and green building materials is given in Section 4.11.) In addition, the framework occupies a portion of the storage volume and the surface area of the insulation is increased as compared to the external frame, internal insulation technique. Furthermore, the insulation is susceptible to sudden changes in weather conditions, causing thermal shock.

Table 5 provides a comparison of the advantages and disadvantages of the two basic support structure techniques.

Table 5: Advantages and Disadvantages of Internal and External Support Structures.

Source: (IIR 1993)

External Support Structure	Internal Support Structure			
ADVANTAGES				
No internal obstructions, therefore storage is easier	Less distortion of the frame since it is protected from temperature variations			
Less surface area to insulate	·			
Easier to install a vapor retarder	Less maintenance of the frame since it is protected from climatic conditions			
Less losses due to direct sunlight	No thermal bridges exist since components of the refrigeration system can be hung from the frame			
Frame is accessible from outside, easy to install				
dock canopies	Ease of installation of false ceilings and split-level floors			
Frame can be made of regular steel				
· ·	Frame can be designed to hold up insulation			
DISADVA	ANTAGES			
Requires added maintenance due to the exposure of the frame to the climate	Larger volume to be cooled			
	Needs more insulation, and insulation is not			
Frame could distort more as it is exposed to variations in temperature, unless features to	protected from climatic elements			
prevent this are added to the design	Frame causes obstruction			
Due to inaccessibility of the frame from the inside, installation of refrigeration components is more complex	More complex methods needed to fix the frame to the foundation			
Larger structures require thermally isolated internal framing.				

4.2.2 Vapor Barrier

It is obvious that the insulated envelope restricts the heat transfer from the warm, ambient environment to the cold refrigerated space. Perhaps less obvious is that the insulated envelope must be impermeable to water vapor in order to prevent the migration of water vapor from the warm ambient environment to the cold refrigerated space (Becker and Fricke 2005). Failure to prevent this migration of water vapor results in condensation of water on the interior of the refrigerated space as well as the formation of ice. According to ASHRAE, "the success or failure

of an insulated envelope is due entirely to the effectiveness of the vapor retarder system in preventing water vapor transmission into and through the insulation" (ASHRAE 2010a).

The transmission of water vapor through the insulated envelope results in the following effects which are detrimental to the refrigerated facility:

• Increased Energy Cost

-The water vapor, upon reaching the evaporator coils, forms a layer of frost. This frost then acts as an insulator, degrading the system efficiency. In addition, the frost may even cause the evaporator unit to become inoperative. Furthermore, energy is eventually required in the defrost cycle to remove the frost from the coils.

Diminished Insulating Effect

-Migration of water through the insulation material may reduce the thermal resistance of the insulation and destroy both the mechanical and thermal performance of the envelope.

Structural Damage

-At temperatures below freezing, water may condense and freeze. The freezing water expands and induces pressure on the structure, causing structural damage.

• Biological Growth

-Moisture, which is trapped within walls or on surfaces, can lead to bacterial and fungal growth.

• Formation of ice in or on the product

All of these undesired effects can be prevented or reduced with the proper installation of a vapor retarder.

Water vapor transmission is caused by the vapor pressure difference across the insulated envelope. Figure 5 shows the temperature gradient (a) and the water vapor pressure gradient (b) in a wall which has no vapor retarder. From the figure, it can be seen that condensation begins within the wall when the 'water vapor pressure' and the 'saturation pressure based on temperature', are equal (c).

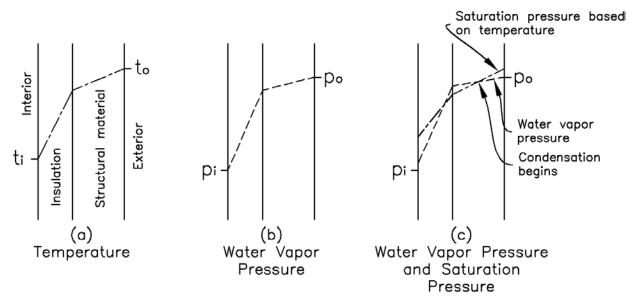


Figure 5: Condensation Due to Temperature and Water Vapor Pressure Gradients in a Wall.

Source: (Stoecker 1998)

In order to prevent moisture migration through an insulated envelope, a vapor retarder must be located on the warm side of the wall. The vapor retarder ensures that the water vapor pressure will remain lower than the saturation pressure throughout the wall, as illustrated in Figure 6. Thus, with the vapor retarder in place, it can be assured that water vapor infiltration will be negligible and that no condensation will occur within the wall.

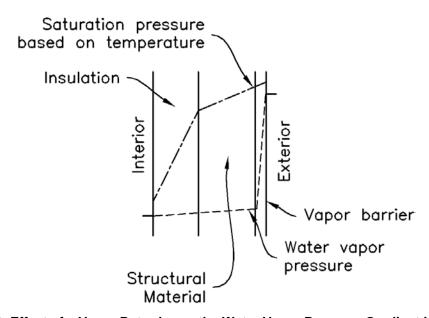


Figure 6: Effect of a Vapor Retarder on the Water Vapor Pressure Gradient in a Wall.

Source: (Becker and Fricke 2005)

It is of great importance to ensure that there are no discontinuities in the vapor retarder at surface interfaces, such as the interfaces between a wall and the floor, or a wall and the ceiling, and at penetrations through the insulation. The failure of vapor retarder systems for refrigerated facilities is almost always due to poor installation. The contractor must be competent and experienced in the installation of vapor retarder systems to be able to execute a vapor tight system. Due to the critical nature of the vapor retarder, the owner should exercise great care in reviewing the work done by the contractor. Thus, the entire vapor retarder/insulation envelope should be completely inspected both during and after installation by a qualified inspection services firm.

To reduce the possibility of condensation within wall or ceiling sections, the individual elements interior to the vapor retarder must be of increasing permeability towards the interior of the refrigerated room to allow for the migration of moisture. Ice formation within freezer walls could be possible if such precautions are not taken. Increasing permeability towards the inside (cold side) of the refrigerated facility is <u>very important</u> to reduce insulation deterioration due to moisture migration.

Types of Vapor Retarders

Vapor retarders may be categorized into three main types (IIR 1993):

- Plastic Coatings or Thin Fluids.
 - -Examples of materials in this category are asphalt, bituminous emulsions and polymer resins. These types of vapor retarders are applied on the exterior surface of the insulation, usually before the insulation is installed.
- Sealing Sheets.
 - -Examples of materials in this category include asphalt paper, plastic sheets and metal films. These materials can be applied in one of two ways depending upon the specific construction techniques used. If the refrigerated facility is constructed using an external support structure, the insulation is on the inside of the structural supports and thus, the vapor retarder is placed between the insulation and the structural supports. On the other hand, if an internal support structure is used, the insulation is on the outside of the structural supports and thus, the vapor retarder is placed on the outside surface of the insulation.
- Prefabricated Sandwich Panels.
 - -Due to ease of installation, the use of prefabricated sandwich panels is quickly gaining popularity in the refrigerated storage facility industry. The external metal surface of the prefabricated panels becomes the vapor retarder. When using prefabricated sandwich panels, care should to be taken to ensure continuous and uninterrupted joints between the panels. Such panels shall be designed to provide inside (cold side) permeability.

Rating of Vapor Retarders

In the rating of vapor retarders, two terms are of importance: permeability (perm-in or kg Pa⁻¹ s⁻¹ m⁻²). Permeability is a material property and

is given in terms of a unit thickness of the material. Permeance is the permeability divided by the actual thickness of the vapor retarder. Vapor retarders are rated according to permeance, where, according to Webber (Webber 1995), "Permeability reflects that material's ability to allow passage of a certain number of grains of moisture (one grain = 1/7000 lb) per inch thickness of material per square foot per hour per inch of mercury of water vapor pressure differential."

For example, if a material is rated with a permeability of 1.0 perm-inch, then for a 2-inch thickness of the material, the permeance is 0.5 perms. Table 6 gives the permeance of several materials. Note that the lower the perm value, the more effective the vapor retarder. In addition, Table 7 gives the relative installed cost for a polyethylene film vapor retarder (IARW 1995).

One of the most important considerations to make before installing the vapor retarder is to determine the thickness of the retarder. While economics are a factor, the retarder must be thick enough to endure the rigors of installation and maintain its integrity. Modern vapor retarder materials, such as polyethylene, have the ability to move without becoming discontinuous when a building shifts or settles. This was not the case in the past when corkboards were used as the standard low temperature vapor retarder.

Table 6: Typical Permeance Values for Selected Materials.

Source: (IARW 1995)

Material	Permeance, perm (10 ⁻¹² kg Pa ⁻¹ s ⁻¹ m ⁻²)	
Polyethylene Film, 8 mil (0.20 mm)	0.04 (2.29)	
Polyethylene Film, 10 mil (0.25 mm)	0.03 (1.72)	
Butyl Rubber Membrane, 48 mil (1.22 mm)	0.042 (2.40)	
Butyl Rubber Membrane, 60 mil (1.52 mm)	0.032 (1.83)	
4 ply Built-Up Roof (Typical)	0.007 (0.40)	
Concrete Block, 8 inch (20 cm) thick	2.4 (137)	
Reinforced Concrete Slab, 8 inch (20 cm) thick	0.4 (22.9)	
Portland Cement Plaster, 3/4 inch (19 mm) thick	11 (629)	
Exterior Grade Plywood, 1/4 inch (6.35 mm) thick	0.7 (40.0)	
Aluminum Foil-Mylar Laminate	0 (0)	
Asphalt Paint	0.4 (22.9)	
Hot Melt Asphalt, 2 oz. ft ⁻² (0.61 kg m ⁻²)	0.5 (28.6)	

Table 7: Installation Cost of Polyethylene Film (circa 1995).

Source: (IARW 1995)

Film Thickness, mil (mm)	Relative Installed Cost, dollars per square foot (dollars per square meter)
4 (0.10)	\$ 0.190/ft ² (\$ 2.05/m ²)
6 (0.15)	\$ 0.197/ft ² (\$ 2.12/m ²)
8 (0.20)	\$ 0.211/ft ² (\$ 2.27/m ²)
10 (0.25)	\$ 0.233/ft ² (\$2.51/m ²)

Note that two thin layers of film are not always as good as one thick layer, since there would be twice as many chances for failure of the vapor retarder and it would require twice the labor, seals and joint laps.

General Guidelines for Vapor Retarder Installation

The following are general guidelines for the installation of vapor retarders. These principles are applicable to all types of vapor retarder materials (IIR 1993).

- Vapor retarders must always be applied on the warm side of the insulation.
- To maintain its integrity, the vapor retarder must be able to withstand the rigors of
 installation and also the stresses imposed on it during the repeated expansions and
 contractions which occur during its service life.
- The vapor retarder must have as few discontinuities as possible. The main areas of concern are at the surface interfaces/junctures between floors, walls and ceilings, and at penetrations through walls, ceilings and floors.
- The vapor retarder should encompass the entire facility.
- The design and manufacture of the vapor retarder should be kept simple. This helps to ensure correct installation of the retarder. Also, the application or installation procedures must be reasonable.
- The installed vapor retarder should be completely inspected by a qualified inspection services firm.

Modern Techniques

Currently, the use of prefabricated insulated metal-skin panels is gaining popularity with designers and contractors. The exterior metal skin of these panels acts as a vapor retarder.

Most insulated panel manufacturers have methods of continuing the vapor retarder from one panel to another, however, there are still the surface junctures/interfaces to consider. The wall to ceiling/roof interfaces are by far the most critical, and many facilities with infiltration problems have discontinuities at these locations (Webber 1995).

To help minimize the problem associated with wall to ceiling/roof interfaces, it is wise to have the insulation contractor be responsible for total vapor retarder continuity rather than the roofing contractor. It is also good design practice to keep the vapor retarder system separate from the insulation materials used, unless the insulation is monolithic (without joints or cracks) and has the required permeance value (Webber 1995).

Since the cost of vapor retarders is a small portion of the total construction cost of a refrigerated storage facility, it makes sense to thoroughly design this aspect to ensure an adequate vapor retarder system. Also, the success of the facility is largely dependent upon the vapor retarder system. As stated by Webber (1995), "there are three major factors which contribute to the success of a refrigerated facility. These are 1) vapor barrier, 2) vapor barrier, and, 3) vapor barrier. One should not be caught looking past the obvious." Thus, the entire vapor retarder/insulation envelope should be completely inspected both during and after installation by a qualified inspection services firm.

4.3 Passive Thermal Design

4.3.1 Thermal Mass (High-Mass) Building Systems

In the high-mass building technique, the walls of the refrigerated facility are composed of an insulation core sandwiched between two concrete panels. The interior concrete layer acts as a structural support for the roofing system, or, alternatively, an interior steel structure may be used to support both the roof and walls. The joints between adjacent panels are filled with spray insulation and caulked to create an air/moisture tight joint resulting in reduced infiltration. The panels are resistive to break-ins and impact damage, and the mass of concrete on the interior of the facility reduces temperature fluctuations from both internal and external loads. Thus, peak loads are lowered, which may help reduce the amount of refrigeration equipment required.

4.3.2 Cool (High Albedo) Roofs

The roof of a single story refrigerated storage facility of 50,000 ft² or greater results in a significant solar load which can be substantially reduced through the use of a cool roof. The California Energy Commission reports that cool roofs can cut solar loads by up to 20 percent through the use of reflective materials that limit solar heat gain.

A cool roof reflects large portions of incident sunlight and thus, a cool roof exhibits reduced roof surface temperature as compared to a regular (hot) roof. The lower roof surface temperature, in turn, leads to reduced heat conduction into the building, thereby lowering the cooling load (Akbari, Levinson, and Rainer 2005). In addition, since the heat gain through the roof of a building peaks in the late afternoon, when summer electricity use is the highest, the use of a cool roof can reduce the building's peak electricity demand (Levinson et al. 2005). Research has shown that energy savings from the use of cool roofs are the greatest for buildings

located in climates with long cooling seasons and short heating seasons, such as that in California.

It has been suggested that a cool roof may reduce the thermal stress on the roof structure and thus increase the lifetime of the roof, thereby reducing maintenance and waste (Akbari, Pomerantz, and Taha 2001). Cool roofs also reduce the outside air temperature and thus increase outdoor comfort and reduce urban smog formation (Levinson et al. 2005).

Akbari et al. (2005) monitored the energy use of several commercial buildings in California before and after the installation of cool roofs. For a cold storage facility located in Reedley, California, they found that the daily energy savings ranged from 70 to 80 Wh/m² when a cool roof was installed on the facility. Akbari et al. (2005) also estimated that the use of cool roofs on similar cold storage facilities in all 16 climate zones of California would result in energy savings ranging from 4 to 8 kWh/m² per year.

For non-residential buildings with low-sloped roofs, Levinson et al. (2005) report that the typical cost premium for a cool roof is 0.00–2.20 \$/m² and cool roofs with premiums not exceeding \$2.20/m² are expected to be cost effective in California climate zones 2–16. In addition, cool roofs with cost premiums not exceeding \$1.90/m² are expected to be cost effective in California climate zone 1.

4.4 Roofs

The roofs of all structures are subject to failure due to water and vapor leaks. The roof of a cold storage facility has to operate under extreme conditions, which further increases the possibility of failure. The designer of the cold storage facility has to satisfy four important criteria to ensure the success of the roof system:

- Structural integrity must be maintained at all times.
- All joints must be carefully sealed to prevent air and moisture infiltration.
- An uninterrupted vapor retarder is required.
- Structural details must be appropriate to withstand applicable seismic forces.

4.4.1 Roof Design

The design of the roof depends on the type of support structure and insulation technique chosen (Becker and Fricke 2005). There are three options at the disposal of the designer:

- External frame, internal insulation.
- Internal frame, external insulation.
- Suspended ceiling.

The roofing designs for these structures are discussed in the following sections.

External Frame, Internal Insulation

In the external frame, internal insulation construction technique, the frame for the roof supports the ceiling insulation on its underside. When performing design calculations for this type of construction, it should be noted that considerable stresses may be imposed on the ceiling and wall panels due to decreased room pressure caused by reductions in room temperature, such as those which might occur during an initial cool-down, or after a defrosting period. Thus, the ceiling insulation must be sufficiently fastened to the underside of the roof supports to prevent the insulation from breaking free and falling downward. If standardized construction elements such as insulated panels are used, careful attention must be taken to ensure that these elements and their fastening mechanisms can withstand the stresses due to changes in room pressure.

To prevent leakage at roof ridges, it is necessary that these joints be sealed properly. The use of flat or corrugated material which is laid over these joints is recommended. The designer also has to ensure that the gutters are adequate (IIR 1993).

Internal Frame, External Insulation

The roof design for internal frame, external insulation construction is more difficult to implement due to the fact that the insulation must be laid over the frame of the roof and be properly connected to the outer wall insulation. In addition, the roof of an internally supported facility must incorporate an incline to provide proper water drainage. Some common problems and complications associated with the internal support, external insulation technique include (IIR 1993):

- Movement and warping as a result of severe weather and temperature variations requires flexibility of the insulation.
- Effective seals must be made at the connection points between the structural barriers and the gutters/downpipes to prevent leaks.
- To prevent the insulation from coming apart due to strong winds, it must be properly fastened to the load bearing structures and the structural barriers.
- Effective seals must be made at the outer connections of the vapor retarder and at the edges of the insulation to prevent leaks.
- Effective design for applicable seismic forces.

Suspended Ceiling Method of Construction

The suspended ceiling method of construction allows for a complete vapor and thermal envelope. In this method, insulation is suspended above the refrigerated space by hanger rods which are fastened to the structural support system, instead of being attached to the structural ceiling. The insulation then acts as a suspended ceiling for the refrigerated space with an air space between the insulation and the exterior roof. If the suspended ceiling is built with sufficient headroom and live load capacity, the area above the ceiling may then serve as a maintenance and utility platform. This type of design is particularly appealing above food processing or hygienic spaces.

It is essential that the space above the suspended ceiling be well ventilated. This ventilation should be controlled by means of a thermostat and roof mounted humidistat sensing outdoor conditions. Near ambient conditions in the space are required to prevent condensation and deterioration of the vapor retarder materials. ASHRAE recommends that a minimum of six air

changes per hour be maintained. The designer also has to ensure that a permanent seal is placed around all penetrations into the space above the ceiling, including columns, conduit and insulation hanger rods.

4.4.2 Roof and Wall Sections

Properly executed roof and wall junctures are critical to the success of the roofing system since these junctures are very prone to leakage. There is a myriad of different construction techniques available for roof and wall junctures, and most insulated panel manufacturers have a preferred method for joining roofs and walls together. A simple conceptual design is discussed in this section (Becker and Fricke 2005).

Figure 7 shows one concept of roof/wall construction. As shown in the figure, this is an example of the internal frame, external insulation technique where the insulation is supported by beams. The vapor retarder is installed on the warm side of the insulation. To ensure the integrity of the vapor retarder, it should extend down a short distance from the roof and then be sealed. In some instances, the use of a roof curb, shown in Figure 8, may be desired to direct the flow of water into drains.

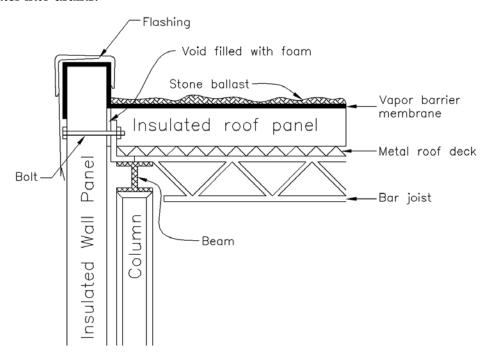


Figure 7: A Wall/Roof Junction.

Source: (Becker and Fricke 2005)

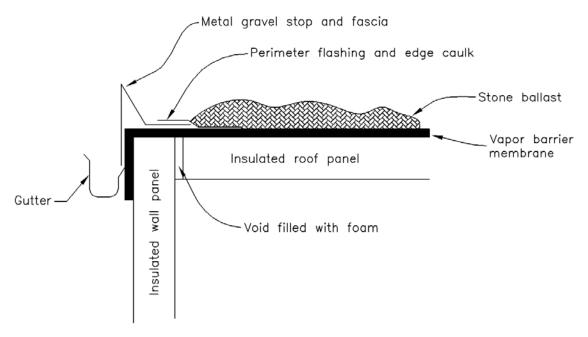


Figure 8: Roof Curb.

Particular attention should be paid to the area between roof beams and insulated wall panels. This space typically does not receive adequate air circulation. Subsequently, heat transfer through the insulation warms the air trapped in this space. Condensation may occur when this warm, moist air makes contact with nearby cold surfaces. To eliminate stagnate air and condensation problems in this area, it is recommended that the space be filled with insulating material.

4.4.3 Roof Guidelines

Several guidelines have been provided by the IARW to assist designers and owners of cold storage facilities in the design and construction of an effective and successful roofing system (IARW 1995):

- Carefully review roof specifications before bids or construction plans are made.
- Verify that the thickness of the insulation specified is appropriate for the storage temperatures involved.
- Ensure that the pitch of the roof is adequate for proper water drainage.
- Ensure that the downspouts and gutters are adequate for the design conditions.
- Roof drains should not be placed through a freezer. If roof drains must be placed through a freezer, ensure that the drains are properly insulated and heated.
- Review, in detail, all types and spacing of expansion joints.
- Use light colored stone ballast (i.e. marble, rock, or gravel) on the roof to improve reflectivity.

- Ensure that roofing felts run perpendicular to the joints of rigid overdeck insulation boards, if used.
- Install a vapor retarder, with a perm rating of 0.01 (5.7 × 10⁻¹³ kg Pa⁻¹ s⁻¹ m⁻²) or finer, on the warm side of the insulation.

4.5 Walls

The walls of a cold storage facility fall into two basic categories: external walls and internal walls. Both provide a barrier between two environments. However, external walls must also withstand loadings imposed by the external environment, such as wind and rain. An important consideration with any wall construction is that penetrations should be kept to a minimum and be properly sealed.

4.5.1 External Walls

External walls could be made of insulated panels, masonry, or concrete. The current trend in the industry is to use preformed materials such as prefabricated insulated panels, corrugated aluminum sheets or plastic-coated steel sheets and pre-cast concrete panels (IIR 1993). Regardless of the material chosen for the exterior walls, the thermal performance of the various wall components should be evaluated.

4.5.2 Internal Walls

The insulation configuration of a refrigerated storage facility depends upon the temperature of its various storage rooms. If the cold rooms are all at the same temperature, one configuration is to have the perimeter of the cold store insulated, with no insulation between the cold rooms. However, if the cold rooms are at different temperatures, the alternative configuration is to have each cold room insulated individually.

If each cold room is insulated individually, then it would be advisable to build the cold room walls using prefabricated insulated panels (IIR 1993). These panels should be freestanding and extend the entire height of the room. In addition, to ensure that the insulation of the rooms is uninterrupted, it is suggested that the ceiling and floor be grooved to accept the ends of the insulated panel. These grooves allow the insulation of the interior walls to be joined to that of the floor and ceiling without creating any thermal bridges. The ease of construction for this method is increased when the external frame, internal insulation technique is used.

ASHRAE recommends that a double column arrangement be used where interior freezer insulated partitions are necessary (ASHRAE 2010a). In this technique, the partition walls are restrained on both sides by columns and girts, and thus, penetration of the wall by structural members is eliminated.

If fire walls with foundations are used to partition freezer rooms, it must be ensured that the foundations are properly heated to avoid frost heaving (IIR 1993).

4.5.3 Horizontal Wall Supports

Usually, intermediate horizontal supports between the floor and ceiling supports are not needed if prefabricated insulated wall panels are used. This is especially true when the

thickness of the panel required for thermal resistivity is larger than that required for structural support (IACSC 1999b).

However, horizontal wall supports are necessary when the walls of the cold storage facility are extremely tall. In this situation, the horizontal wall supports are used to align and strengthen the horizontal butt joints in wall panels that occur when the manufactured length of the panel is less than the height of the wall.

Horizontal wall supports also control the stress deflections induced by wind loading and the 'thermal bowing' that results from the difference in temperature across the thickness of the panel (IACSC 1999b). Wall support framework is also required where seismic forces are applicable.

4.6 Floors

The ground-floor slab of a cold storage facility is critical to the effective operation of the facility (Becker and Fricke 2005). The following considerations must be taken into account by the designer of the facility to ensure a successful floor design (Williamson 1996):

- A soils engineer should be retained to provide proper soil preparation and applicable soil load data.
- The floor must be able to support the applied loads without any deformation or cracking.
- The number of exposed joints in the floor must be minimized.
- The joints must be maintenance free and should not impede fork lift truck operating speeds.
- The floor must be highly abrasion resistant to minimize the formation of dust and maximize the service life of the surface.
- The floor must not be slippery and should be smooth and easy to clean.
- The floor design should have some flexibility to allow for possible changes in the future. In addition, floors may be "grooved" between storage sections to accommodate movable partitions.

4.6.1 The Foundation

The foundation of the facility and the soil below it must be designed to withstand the compressive loads that are applied to it, typically in the range of 1000 lb ft² to 1500 lb ft² (48 kPa to 72 kPa). This is a stationary load that is composed of the weight of the stored products and the structural elements. The foundation is also subjected to concentrated rolling loads usually from forklift trucks. These loads are about 6000 lb (27 kN), or about 2000 lb (9 kN) per wheel (IIR 1993). The floor slab must have the ability to distribute these rolling loads uniformly over the foundation and to the soil, engineered fill and/or pilings.

After the foundation and floor slab have been poured, the floor should be sealed and the concrete should cure for at least 28 days before the temperature within the storage facility is reduced to operating conditions. Also, joints should be sealed with flexible caulk. Furthermore,

joints should not be used in doorways. Instead, a continuous slab should extend approximately two feet through the doorways and under-floor heating should be used where necessary near doorways to prevent condensation and ice formation in these areas.

For storage of products above freezing, it may not be necessary to provide insulation below the wearing slab of the floor since the ground would provide adequate thermal insulation. However, for storage below freezing, it is necessary to insulate the cold room floor to reduce the possibility of damage to the facility due to 'frost heaving,' the expansion of frozen soil beneath the floor. In addition, a floor heating system is usually needed to avoid frost heaving.

For a single floor cold store, with the insulation installed inside of the frame, the foundation is usually constructed as a raft that includes beams around the edges to support the structural frame of the facility (IIR 1993). This raft is placed directly above the ground. Care must be taken if the subgrade consists of stones and pebbles. It is recommended that these materials be removed, since they can promote the capillary movement of water into the area directly below the floor, possibly resulting in or aggravating frost heaving. An alternative method of overcoming the frost heaving problem is to construct the load-bearing slab in such a manner that there is an empty space between the ground and the slab.

When the insulation is installed on the exterior of the frame in cold rooms which operate below freezing, thermal isolation blocks which support the structural members of the facility must be installed to minimize the thermal paths to the ground. It is recommended that materials of low thermal conductivity and adequate mechanical strength be used for the thermal isolation blocks. Heating devices can also be installed around the footings.

4.6.2 Frost Heaving

Frost heaving occurs when the ground below a cold store drops below freezing temperatures. This causes the moisture in the ground to freeze and expand. The expansion of the moisture results in tremendous pressures being exerted on the floor, causing the floor to buckle under the load. In addition, the columns which support the roof of the facility may shift or move due to the heaved floor, causing damage to the roof as well as the support structure. Frost heaving can cause catastrophic damage to the refrigerated facility and is usually very expensive to repair. It is essential for the designer of the refrigerated facility to consider methods of preventing frost heaving of the floor during the design stage.

Frost heaving can usually be prevented with a proper under-floor heating system, which would prevent the subsoil from freezing. Figure 9 shows an illustration of the frost heaving phenomena.

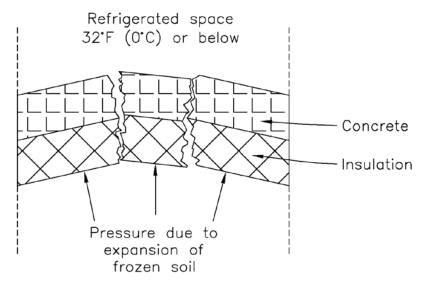


Figure 9: Floor Damage Due to Frost Heaving.

For frost heaving to occur, three conditions must exist (IARW 1995):

- Freezing soil temperatures.
- A water source.
- A subgrade that supports capillary movement of water.

The absence of any one of these conditions reduces the possibility of frost heaving but does not eliminate it. Insulation does not prohibit the flow of heat, but merely slows the rate of heat transfer. Thus, even an insulated floor may be damaged by frost heaving. However, using materials that have a low thermal conductivity with the appropriate thickness and compressive strength will practically eliminate frost heaving when used in conjunction with a properly designed and maintained floor heating system (IARW 1995).

The following are various methods that can be used to prevent frost heaving of floors (IARW 1995):

- Heating of the ground below the floor to prevent freezing temperatures.
- Removal of existing soils which support capillary movement of water.
- Sufficiently lower the ground water level in the area of the refrigerated storage facility.

4.6.3 Under-Floor Heating Systems

The addition of supplemental heat to the sub-floor strata is effective in eliminating the phenomena of floor heaving. Typical methods of supplemental heating include liquid circulation (wet systems) through buried tubes, electrical resistance heaters placed within the sub-floor strata, and both gravity driven and fan driven air circulation through buried pipes (air vents).

Liquid Circulation (Wet) Heating Systems

Liquid circulation heating systems, shown in Figure 10, utilize heated liquids such as glycol solutions or oil to provide supplemental heating to the subsoil below the floor of the facility (IARW 1995). In this system, piping is installed in a sand fill material which is then covered by a vapor retarder, insulation and the concrete floor.

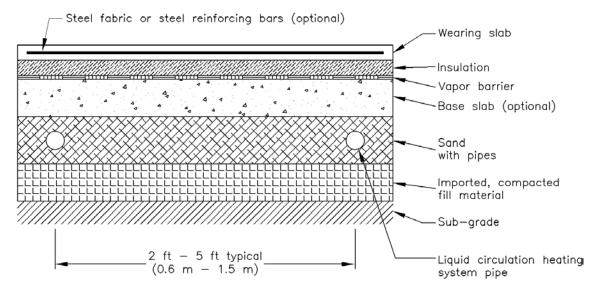


Figure 10: Typical Cross-Section of a Floor with Liquid Circulation Heating.

Source: (Becker and Fricke 2005)

The liquid (usually 30 percent to 40 percent propylene glycol) is heated and then circulated through the buried pipes to provide even heating to the sub-floor. The use of a heat exchanger and a pump are required to achieve this. For energy efficiency, it is recommended that waste heat from the refrigeration system be used to heat the circulated liquid.

The liquid circulation floor heating system provides an even heat distribution to the sub-floor when properly controlled and monitored. A disadvantage of using such a system is that, on very rare occasions, leaks may develop, and these leaks tend to be difficult to locate and repair. Thus, an environmental and maintenance risk is associated with under-floor heating systems using circulated glycol (Pacific Gas and Electric Company 2006). Also, when leakage occurs, the entire system is affected and this may result in local cold spots and heaving. Fortunately, when the heating system is properly installed with no joints under the floor and thoroughly pressure tested prior to covering with the upper layers of the floor, leaks are very rare. A double loop, redundant system may be installed to insure against failure. Wet systems are also flexible and they allow for expansion.

Electrical Heating Systems

Electrical heating systems, shown in Figure 11, make use of resistance-heating cables that are placed in the sub-floor of the facility. The resistance-heating cables should be installed in a conduit placed in the sub-floor. This allows for easy maintenance and replacement of faulty heating elements. Furthermore, when the heating elements are connected in parallel, only the

faulty zone would be affected and the rest of the circuit would continue to function. This is an enormous advantage of using such a system.

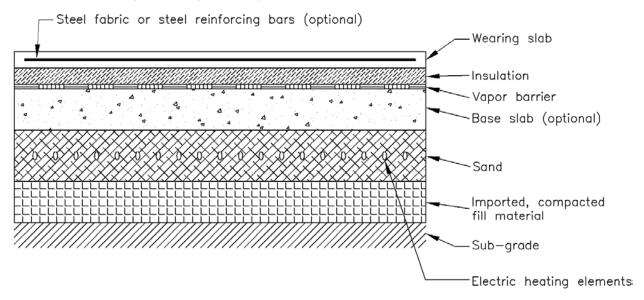


Figure 11: Typical Cross-Section of a Floor with Electrical Heating.

Source: (Becker and Fricke 2005)

Typically, resistance heating cables are operated at a fraction of their rated capacity, thus greatly reducing the likelihood of failure. These electrical heating systems can be controlled either by a thermostat or by a resistance temperature device (RTD). Both of these devices are placed in the conduit to sense the temperature of the sub-floor. The advantage of using RTDs is that they have the ability to limit the cable's power output to closely match heat loss (IARW 1995). Electrical heating tends to be expensive to install as well as expensive to operate. On the other hand, electrical heating systems are easily expanded.

Air Circulation Heating Systems

Air circulation heating systems can be either gravity driven or fan driven systems.

Gravity Driven Air Circulation Heating Systems

If properly designed and constructed, gravity driven air circulation heating systems are effective in preventing floor heaving and are energy efficient. However, they are only practical in mild or warm climates since ambient air is ineffective at heating the floor when the outside temperature is below freezing.

Typically, ventilation pipes with an inside diameter ranging from 4 inches to 8 inches (0.1 m to 0.2 m), are installed on 6 foot (2 m) centers, 12 inches to 16 inches (0.3 m to 0.4 m) below the sub floor, as shown in Figure 12. Pipe material is typically concrete, although polyvinylchloride or asphalt impregnated fiber pipe may be used. As shown in Figure 13, the elevation of the intended inlet of these ventilation pipes should be at least one pipe diameter above the elevation of the main run and slope downward to meet the main run which should be sloped downward toward the outlet. This will establish the direction for the airflow. The cold, dense

air beneath the floor flows down the slope and spills from the pipe outlet, drawing in warm ambient air at the inlet. A continuous flow of air is created which tempers the sub-floor strata and prevents floor heaving (Stoecker 1998; Powers 1981).

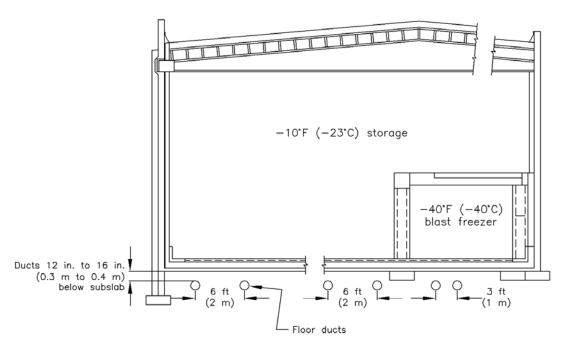


Figure 12: Typical Under-Floor Ventilation Pipe Placement.

Source: (Becker and Fricke 2005)

Fan Driven Air Circulation Heating Systems

Forced air circulation systems are similar to the gravity driven systems with the addition of blowers or fans to improve the air circulation.

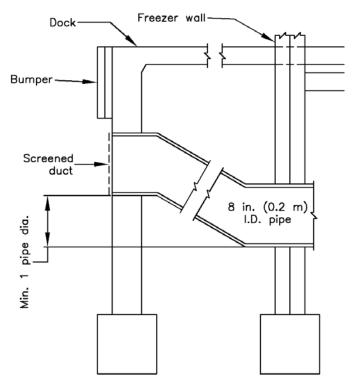


Figure 13: Detail of Under-Floor Ventilation Pipe Inlet.

For proper operation of air circulation heating systems, it is important to prevent blockage of the pipe inlets and outlets as well as the pipes themselves. Screens should be placed over the inlets and outlets to prevent entry of debris and rodents, and these screens should be checked regularly to remove any accumulated debris. A regular maintenance inspection of the air movement through each pipe should be performed in order to quickly remedy any pipe plugging which might occur.

During the winter season when the ambient temperature drops below $32^{\circ}F$ (0°C), the ventilation pipes should be plugged. At least a 2-inch (50 mm) thick plug of insulation board should be installed in all pipe openings exposed to the weather. Once the ambient temperature during the day is above $32^{\circ}F$ (0°C), the plugs may be removed. It should be stressed to maintenance personnel that failure to plug ventilation pipes when the ambient temperature drops below $32^{\circ}F$ (0°C) may cause significant damage to the floor of the facility if left unattended.

If an air circulation heating system fails to function properly, the ventilation pipes may become blocked by frozen water and floor heaving may occur. Inadequate airflow may cause such a problem and the use of centrifugal fans may be necessary to supply the proper airflow through the ventilation pipes. If forced air circulation is insufficient to remedy the situation, the use of electrical resistance heating or high pressure, high temperature kerosene-fired blowers may be required.

Air circulation heating systems, both fan and gravity driven, tend to be high maintenance and they are not readily expandable. Also it should be noted that the amount of heat delivered by such systems cannot be controlled. Thus, these systems tend to work well in mild climates. It is recommended that the advice of an experienced facility design engineer be sought when assessing the feasibility of using gravity driven or fan driven air circulation floor heating systems.

4.6.4 Additional Measures for Reducing Frost Heaving

The following steps are recommended to prevent moisture migration through capillary action (IARW 1995):

- Remove existing soil and replace with an impervious material.
- Use coarse, granular sub-floor fill.
- Construct a suspended slab floor, or, for example, a basement.

In addition, since frost heaving is caused by moisture, lowering or eliminating ground water would essentially prevent frost heaving. However, doing so is usually difficult and cost prohibitive.

If the only possible location for the floor of a refrigerated storage facility is at the ground water level, then the floor should be built on stilts or columns with an air space between the grade and the floor. In such a situation, the floor must be capable of supporting both structural and product loads.

4.6.5 Under-Floor Heating Systems Utilizing Waste Heat

Potential applications for using waste heat from an industrial refrigeration system include under-floor heating as required for freezers, cleanup water pre-heating, domestic water heating, boiler makeup water heating, and space heating (for both temperature and humidity control) (Reindl and Jekel 2007).

Many food processing facilities utilize heat rejected from hot compressor discharge gas for under-floor heating via a heat exchanger cooled by a liquid such as a 30 percent to 40 percent propylene glycol solution which is then circulated through buried pipes to provide even heating to the sub-floor (Wilcox et al. 2007). The greatest opportunity to recover heat is through a desuperheater, where water can be heated as high as $100^{\circ}F$ to $120^{\circ}F$ in a circulating loop. Unfortunately, about 10 percent or less of total compressor heat rejection is superheat, so the total heat (Btu's) available for recovery is limited.

If a condensing heat exchanger is installed, water temperature is limited to the condensing temperature which, at 90 psig for ammonia, is only 58°F. Although most of the total rejected compressor heat is released in condensing, the quality of the heat recovery is limited by saturated condensing temperature. In this case, the water could not be heated higher than the 58°F temperature of the condensing ammonia.

In some multi-compressor applications, one or more compressors can be operated at increased discharge pressure to act as heat pumps. In this case, heat recovery from the refrigeration

system may be cost-effective, because compressor heat pumps can produce water temperatures up to 85°F or 90°F.

Several locations within an industrial refrigeration system are candidates for heat recovery, including oil cooling/heat rejection from screw compressors, head cooling in reciprocating compressors, and the high-stage discharge gas stream of reciprocating and screw compressors (Reindl and Jekel 2007).

The heat rejected through a water- or glycol-cooled oil cooler is a good candidate for energy recovery. In the oil cooling heat exchanger, hot oil from a screw compressor's oil separator enters at a temperature near the discharge gas temperature, typically between 71°C to 85°C (160°F to 185°F). The oil is then cooled in the oil cooling heat exchanger to around 54°C (130°F). Assuming a cooling fluid inlet temperature of 13°C (55°F), the cooling fluid could exit the oil cooling heat exchanger at a temperature of around 43°C (110°F). Thus, the temperature of the oil results in waste heat with a moderate quality which could be used for various applications such as under floor heating, domestic water heating and space heating.

There are many situations in which heat recovery is economical, and many others in which it is not (Stoecker 1996). The decision of how and even whether to use heat reclaim can be a tricky one that is based on:

- Relative fuel costs;
- How much of a capital investment is required;
- How much operating cost will be saved;
- Whether the timing of the availability and requirement for heat are coincidental;
- The temperature level of the rejected heat and the temperature level of the heating need.

4.7 Docks

Refrigerated storage facilities present several unique design considerations, such as refrigerated loading docks, vestibule air locks and heated door seals.

Shipping docks are meant to provide space for free movement of goods to and from storage, sorting, packing, inspecting, and in some cases, storage of pallet boxes and idle equipment. Refrigerated docks also keep a great deal of moisture from entering the freezer, and a well-designed and insulated dock can also reduce the refrigeration load significantly, which in turn, provides savings in operating costs for a freezer. For cooler facilities, installation of a refrigerated dock reduces the load on the refrigerating units and assures more stable temperatures (Becker and Fricke 2005).

The dock should at least be 30 ft (9 m) wide. The choice of width mostly depends upon the traffic levels in the facility. Commercial storage facilities require more dock space than specialized facilities, due to the variety of products to be handled and the higher traffic levels.

Another important specification to be considered is the height of the loading dock floor relative to ground level and the vehicles being serviced. Most refrigerated storage facilities have

separate loading docks for trucks and railroad carriers. If railroad cars utilize the dock, then the dock floor must be level with the floors of the railroad cars. Rail dock height and building clearances should be verified by the railroad serving the plant. A rail dock height of 4.5 ft (1.4 m) is typical. This distance does not typically change, since most railroad carriages are of a uniform height.

The truck dock height should be as high as the average height of the over-the-road trucks servicing the facility. Refrigerated trucks usually require a height of 50 inches (1.3 m). However, different truck trailer beds have different heights, and as a truck is unloaded, its height will change. In this scenario, the loading dock may need to be raised and lowered accordingly. This can be accomplished with a dock leveler. Dock levelers span the distance between the variable height of the truck bed and the fixed height of the loading dock floor. There are many types of dock levelers available and the choice of dock leveler should be based on the height difference, load capacity, and service life requirements (IIR 1993; Andel 1998; Gould 1991).

Since refrigerated docks are maintained at temperatures of 35°F to 45°F (2°C to 7°C), and as low as 15°F (-9°C) for ice cream, cushion-closure seals around the truck doorways are necessary to reduce infiltration of outside air. An inflatable or telescopic enclosure can be extended to seal the space between the railcar and the dock.

It is recommended that docks be refrigerated (Stoecker 1998; Colby 1989). This protects the chilled or frozen products in the event that they do not move directly to storage or transport. An appropriate air temperature in the dock area is within the range of 35°F to 45°F (2°C to 7°C). This temperature range is low enough to reduce the infiltration of warmer, moist air into storage areas, thus reducing lower temperature refrigeration loads and increasing the time period between defrosting of the coils. However, it is important not to allow the dock temperature to become any lower, or freezing may occur on the dock floors. To maximize worker comfort, a temperature near the high side of the reasonable range is suggested. The docks should be equipped with refrigerating devices that can lower the temperature and relative humidity as deemed necessary.

Larger cold stores often have enclosed or enclosed and refrigerated docks. This is especially true in cases where the climate is warm, when a product must remain on the dock for an extended period of time, or in situations where delicate goods, such as ice cream, are handled. If a cold store does not need to meet any of these criteria, then an open loading dock may be utilized.

In order to maximize stability of temperature and humidity, the loading dock must be completely insulated. The roof and walls of the dock should be insulated with polyurethane, expanded/extruded polystyrene, glass fiber, or other approved insulating material. Insulated sealing cushions should be placed between the vehicle and the door to the dock. Retractable, inflatable seals are available which provide the most flexibility to accommodate truck levelers, vehicles that may be off center, and vehicles of various sizes and shapes (Cleland 2002;

Frommelt Industries 1989). Dock levelers should be sealed, weather-stripped and fit as snugly as possible.

Dock doors must be sized and placed appropriately to ensure the most efficient operation. The dock floor height and door height should be compatible with the trucks and/or railroad cars that will service the facility.

The ends of the loading dock often provide a convenient location for offices, lavatories, break rooms, and battery-recharge facilities (IIR 1993). The checker's office may be situated so that a view of the entire length of the dock is available. Figure 14 shows a typical cold store, with all these amenities. Figure 15 provides details of a typical truck loading dock.

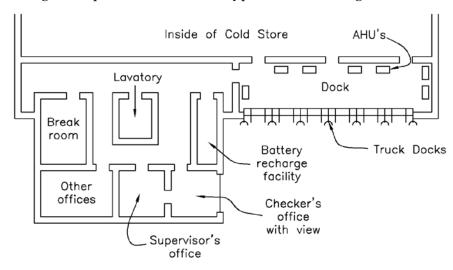


Figure 14: Typical Cold Storage Facility Layout Showing Docks and Miscellaneous Rooms.

Source: (Becker and Fricke 2005)

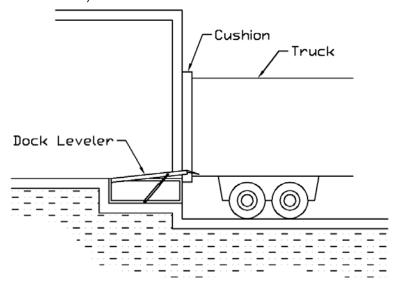


Figure 15: Truck Loading Dock and Leveling Mechanism.

Source: (Becker and Fricke 2005)

4.7.1 Layout and Orientation

Orientation of a cold store's refrigerated dock with respect to the prevailing winds has a significant effect upon infiltration during the loading and unloading operation. By orienting the refrigerated dock so that it does not face into the prevailing wind will greatly reduce infiltration and thereby reduce the refrigeration load and the defrost frequency, ultimately reducing energy costs.

4.7.2 Shading

Refrigerated dock design can lead to significant energy savings. During the loading and unloading operation, proper storage conditions must be maintained within the refrigerated truck by means of its on-board refrigeration system. Significant energy savings can be harvested by providing an extended overhanging roof to shade the truck, thereby reducing its solar load. Additional energy savings can be realized through the use of insulated sealing cushions to reduce infiltration between the truck and the dock door, thereby reducing the infiltration load on both the truck and dock refrigeration systems

4.8 Doors

The doors of a cold storage facility are a key ingredient for a successful facility (Becker and Fricke 2005). Doors can be linked directly to the operational cost and productivity of the facility. The size, location and the type of door selected all exert huge influence on the productivity and the time that the door remains open, which in turn affects the refrigeration load (Stoecker 1998).

This section discusses the various design considerations, selection and problems associated with the doors of a cold storage warehouse.

4.8.1 Door Function

Doors allow for the movement of personnel, equipment and goods to and from the cold store facility. The International Association of Cold Storage Contractors (IACSC) lists the following additional functions that doors must serve in cold storage facilities (IACSC 1999b):

- Doors must provide an escape route in case of an emergency and must always have a manual over-ride of any locking mechanism.
- Doors must be able to maintain the thermal and vapor seals of the refrigerated facility. If a door is used for controlled atmosphere storage, then it must be gas tight.
- Doors must be as fire resistant as the walls of the facility.
- Doors must limit the infiltration of the external environment into the envelope.
- Doors must function properly and reliably in a wide range of temperature differentials, pressure differentials and environmental conditions.
- Doors must be safe to operate for their entire design life and equipped with safety devices such as safety edges and a manual override in case of power outages.

4.8.2 Effects of Doors and Door Openings

In modern cold storage facilities, where products are handled by automatic handling methods and where there is a high volume, rapid turnover of goods, air infiltration through open doors can represent 50 percent or more of the total refrigeration load (IACSC 1999b).

The design and selection of doors used in a cold storage warehouse is always a compromise between material handling requirements and the desire to maintain the controlled environment within the envelope.

Energy losses through doorways are due to the following mechanisms (IACSC 1999b):

- Thermal radiation and conduction through doors and door seals.
- Air infiltration through the interfaces between the door seals and door frames when the door is closed.
- Air infiltration when the door is open.
- Thermal radiation when the door is open.

From the above factors it is obvious that the size and number of doors should be carefully considered since these two factors greatly affect energy loss from the envelope.

The main energy losses are caused by infiltration and conduction. Energy losses through thermal radiation are usually small and thus negligible. Infiltration and conduction energy losses are a function of the following factors (IACSC 1999b):

- Door usage.
- Door construction and material.
- Size of door opening
- Door opening/closing speed.
- Door seal condition/efficacy.
- Temperature differential across the door.

When a door is used infrequently, the main causes of energy loss are conduction through the door and air infiltration through the door seals. If the door seals are ill fitting or are in a poor condition, air infiltration will dominate. For frequently used doors, air infiltration through the door opening will be the dominate source of energy loss.

4.8.3 Minimizing Conduction Losses Through Doors

To reduce energy losses through conduction, the door should be designed such that the thermal resistance of the door in its closed position is similar to that of the walls and ceiling of the facility (Becker and Fricke 2005). However, caution is necessary if this requirement is met by increasing the thickness of the door. With increased door thickness, the door's opening and closing speed becomes slower. Table 8 shows the typical thickness of doors for various operational temperatures and usage frequencies.

Table 8: Door Selection Recommendations.

Source: (Stoecker 1998)

Operational Temperature °F (°C)	Low Frequency Usage (0-100 cycles/day)	Medium Frequency Usage (101-400 cycles/day)	High Frequency Usage (400-1500cycles/day)
50 to 40 (10.0 to 4.4)	Manual hinged or sliding door. 2 inch (51 mm) polyurethane or 3 inch (76 mm) expanded polystyrene panel.	Power operated sliding or fabric door.	High speed sliding or fabric door.
40 to 32 (4.4 to 0.0)	Manual hinged or sliding door. 3 inch (76 mm) polyurethane or 4 inch (102 mm) expanded polystyrene panel.	Power operated sliding or fabric door.	High speed sliding or fabric door.
32 to -10 (0.0 to -23.3)	Manual hinged or sliding door. 4 inch (102 mm) polyurethane or 6 inch (152) expanded polystyrene panel, with trace heating.	Power operated sliding with 4 inch (102 mm) polyurethane or 6 inch (152) expanded polystyrene panel with trace heating.	High speed sliding door with 4 inch (102 mm) polyurethane panel with trace heating.
-10 to -40 (-23.3 to -40.0)	Manual hinged or sliding door. 6 inch (152 mm) polyurethane or 8 inch (203 mm) expanded polystyrene panel, with trace heating.	Power operated sliding with 6 inch (152 mm) polyurethane or 8 inch (203 mm) expanded polystyrene panel with trace heating.	High speed sliding door with 6 inch (152 mm) polyurethane or 8 inch (203 mm) expanded polystyrene panel with trace heating.

4.8.4 Minimizing Air Infiltration Losses Through Doors

Over half of the total heat load of a refrigerated storage facility can be attributed to air infiltration (Chen et al. 2002). In addition, air infiltration represents the major source of frost on evaporator coils. Thus, optimal design and operation of refrigerated storage facilities requires accurate estimation of the air infiltration rate.

Most air infiltration occurs through the doorways of refrigerated storage facilities. Air infiltration also occurs through door seals, wall panel connections and pressure equalization vents, but their contribution to total infiltration is small.

Air Infiltration Through Doorways

The mechanism of air infiltration through doorways is illustrated in Figure 16. Cold air from the refrigerated space escapes the envelope from the bottom of the door opening, allowing for the less dense moisture-bearing warm air to infiltrate the controlled environment at the top of the door opening. At approximately the mid-point of the door height, there is no flow. It

generally takes less than five seconds for this airflow pattern to become fully established (Hendrix, Henderson, and Jackson 1989).

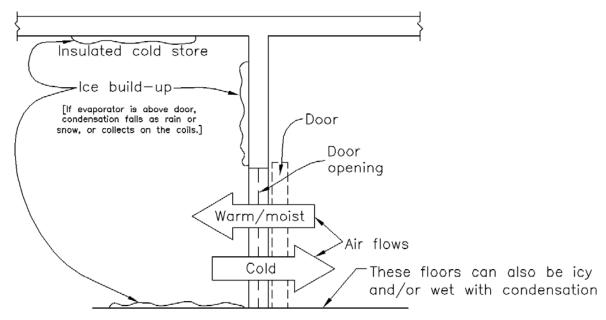


Figure 16: Mechanism for Air Infiltration in a Cold Storage Facility.

Source: (Becker and Fricke 2005)

Infiltration of warm moist air through doorways into refrigerated storage facilities can cause the following problems (Foster et al. 2003):

- Increased cost associated with operating and defrosting the refrigeration system
- Safety problems associated with fog around the door opening and ice forming on the floor, walls and ceiling near the door opening.
- Food safety, quality and weight loss caused by temperature fluctuations.

A mist can be formed in the doorway when the cold air within the storage room comes into contact with the warm moist ambient air. This mist can restrict the field of vision of forklift drivers, resulting in an increased potential for accidents (Foster et al. 2002). Ice can also form around the door opening as well as on the walls, floor and ceiling near the door. The ice which forms around door openings can impede the opening and closing of doors and the ice which forms on the floor can create dangerous conditions for forklift drivers. Furthermore, removal of the ice is labor intensive (Foster et al. 2002).

Thus, to minimize the amount of energy loss due to infiltration through doors, door opening/closing cycles should be minimized, door opening/closing speeds should be relatively fast, and door opening size should be minimized. In addition, devices for impeding airflow, such as PVC strip curtains, air curtains, or vestibules, should be utilized.

PVC Strip Curtains

A common method for reducing infiltration is to utilize transparent PVC strip curtains in conjunction with doors. Strip curtains, which consist of vertical strips of overlapping PVC in a doorway, effectively restrict airflow into and out of the cold storage room. However, to ensure their effectiveness, strip curtains require maintenance. Gaps between vertical strips and tears created from wear should be remedied as soon as possible to reduce energy losses. Formation of ice on the strips can occur and low temperatures may cause the strips to become brittle.

Even though strip curtains can be effective at reducing infiltration, strip curtains are considered to be unhygienic and their use may be prohibited in many food plants, especially USDA inspected meat and poultry plants (Foster et al. 2006). In these situations, strip curtains may be a source of contamination. Also, strip curtains may cause a false sense of security and encourage facility personnel to leave doors open.

Air Curtains

Air curtains consist of a fan unit which produces a jet of air blown vertically or horizontally in front of the door, creating a buffer between the inside and outside of the cold room. The air jet forms a barrier to heat, moisture, dust, odors, insects, et cetera (Foster et al. 2006).

For a vertical air curtain, the fan unit is mounted above the door, blowing the air jet vertically downward, in front of the door, and the air jet impinges on the floor. A portion of the air from the air curtain then enters the refrigerated room and the remaining air flows into the ambient. Thus, there is a slight refrigeration load due to the incoming air from the curtain, but it is much less than that which would occur without any curtain.

Horizontal air curtains are usually of the recirculating type, where a horizontal jet of air, from a fan unit and supply plenum mounted on one side of the door, blows across the doorway to a return plenum on the other side. As compared to the vertical air curtain, the horizontal air curtain provides a stiffer buffer between the cold room and the ambient.

Air curtains reduce infiltration without taking up as much space as vestibules and without impeding forklift traffic (Foster et al. 2006). Advantages of air curtains include good visibility, no physical barrier, and no surface for ice formation.

Air curtains are moderately effective. Air curtains can reduce the mass of air entering the refrigerated storage facility by 38 percent. In addition, computational fluid dynamics (CFD) simulations have predicted that air curtains can reduce the heat gain to the refrigerated storage facility by 84 percent (Foster et al. 2002) It is important to have sufficient air jet velocity so that the air curtain does not break down before it reaches the floor or the return plenum. Careful adjustment of the discharge nozzles is required for optimum performance. In addition, efforts should be made to avoid damage to the air discharge nozzles due to forklift accidents.

Vestibules

Vestibules or air locks may be used to effectively reduce infiltration, especially when the temperature differential between two environments is high. As shown in Figure 17, a vestibule or air lock consists of a short corridor with doors at each end. Ideally, only one door is open at

any time. Vestibules promote significant local mixing of the warm ambient air and the cold refrigerated air, thus reducing mass and heat infiltration into the refrigerated space. In addition, strip curtains and air curtains may be used in conjunction with the doors at each end of the vestibule to further reduce infiltration.

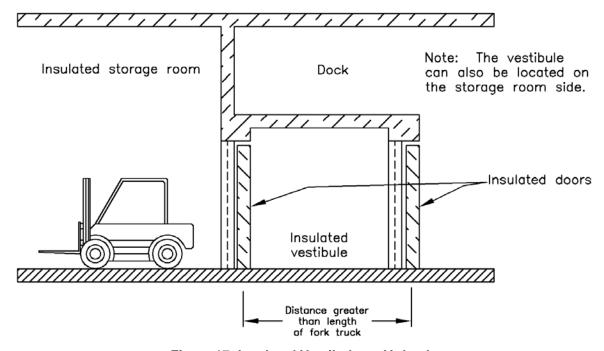


Figure 17: Insulated Vestibule or Air Lock.

Source: (Becker and Fricke 2005)

There are several variations of the vestibule concept illustrated in Figure 17 that are utilized. For example, one concept features side-by-side vestibules for one-way traffic where the number of door opening cycles per day is high. Another solution features a proprietary special "short" vestibule utilizing internal vestibule air recirculation coupled with waste heat energy.

Vestibule solutions should be evaluated carefully to ensure that economic benefits in energy savings justify the capital and maintenance costs. Furthermore, vestibules can also restrict forklift traffic and they take up valuable space which could otherwise be used in the storage or dock areas. In addition, vestibules are difficult to retrofit to existing storage facilities (Foster et al. 2006).

4.8.5 Effectiveness of Infiltration Reduction Devices

To decrease the air infiltration through doorways, various door protection devices, such as strip curtains, air curtains, vestibules, and fast-acting doors, should be used (Chen et al. 2002). The effectiveness of such devices can be quantified as follows:

$$E_p = \left(1 - \frac{Q_{protect}}{Q_{unprotect}}\right) \cdot 100 \tag{2}$$

where E_p is the door protection device effectiveness (%), $Q_{protect}$ is the air infiltration rate for the protected door (m³/s), and $Q_{unprotect}$ is the air infiltration rate for the unprotected door (m³/s).

Single plastic strip curtains have been found to have an effectiveness of 86 percent to 96 percent without forklift traffic and 82 percent to 92 percent with one forklift entry and exit per minute. On the other hand, air curtains have been found to have an effectiveness of 49 percent to 83 percent (Chen et al. 2002).

For refrigerated storage facilities with high frequency forklift movement, rapid-roll and fast-folding doors have been used. These doors usually include automatic opening and closing devices and are fast acting. Such doors typically have an effectiveness of 93 percent without traffic and 79 percent to 85 percent with traffic at a rate of one entry and exit per minute (Chen et al. 2002).

4.8.6 Door Seals

It is imperative that doors in a cold storage facility be kept tightly sealed. Poor fitting doors will result in losses due to air infiltration. Thus, the doors in a cold storage facility should be fitted with seals that are flexible enough to accommodate the effects of thermal bowing of the doors and their supporting structure (Stoecker 1998).

It is recommended that door seals be made of a wear resistant material which can withstand abuse from the opening and closing of the doors. The seals must also retain their material properties at low temperatures (Stoecker 1998). Two materials that meet these requirements, and are thus frequently used as door seals, are Neoprene and silicone rubber.

Sweeper seals can be used on the bottom surface of a door to form an effective seal with the floor, provided that the surface of the floor is smooth and level.

4.8.7 Trace Heating

All door seal systems permit some infiltration of warm, moist air that can form ice on the door seals, causing them to be less effective. In some cases, the ice formation on door seals could render the door inoperative. Thus, door seal heating systems, such as the one shown in Figure 18, should be used to prevent frost buildup on door seals.

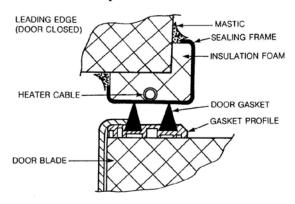


Figure 18: Typical Door Seal and Heating System.

The configuration and power requirement of a door seal heating system will vary according to the type of heater system used and the temperature of the room. However, for safety issues the trace heating system should operate at 55 volts or lower, and should be contained within a fire retardant carrier (Stoecker 1998). This helps to dissipate heat and also to protect the system from lift truck damage.

In addition to trace heating around the door seals, it may be necessary to heat the floor near doorways and/or provide perimeter insulation to prevent frost and ice accumulation in these areas. Frost accumulation on the floor can impede the motion of doors, thus preventing them from fully opening or closing. Also, frost or ice on the floor presents a safety hazard to forklift drivers and other personnel.

4.8.8 Door Size

The doors of the warehouse must be large enough to accommodate the free movement of pallet laden forklift trucks. The standard pallet size is 40 inches (102 cm) wide, and therefore, the minimum width of the door must be at least 6 ft (1.8 m). The door height is also important. Doors should be as low as practical but sufficient to clear the forklift mast in the collapsed position and the forklift operator overhead guard.

There are a large variety of door sizes available from various manufacturers. It is recommended that the designer/owner of the facility consult with these door manufacturers to determine an appropriate door size that best suits the intended purpose, bearing in mind that door size affects opening/closing cycle times.

4.8.9 Door Type

There are two general types of doors available commercially, namely, vertically and horizontally operating doors. Horizontal doors are more commonly used for the high traffic doorways of the facility. Vertical doors are more commonly used for loading docks, since they are more appropriate for this purpose. These doors are usually kept open for the loading and unloading of trucks, provided there are dock door seals between the trucks and loading dock. Figure 19 through Figure 22 illustrate common types of doors used in refrigerated storage facilities.

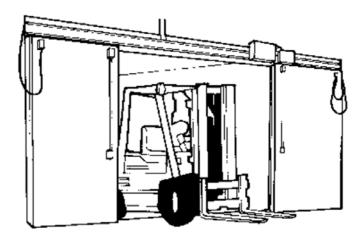


Figure 19: Bi-Parting Horizontal Sliding Door.

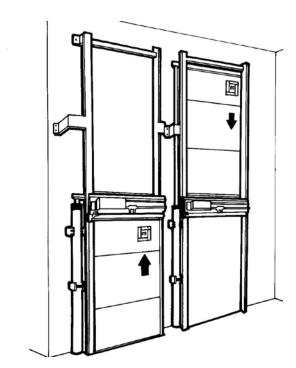


Figure 20: Vertical Sliding Door.

Source: (Becker and Fricke 2005)

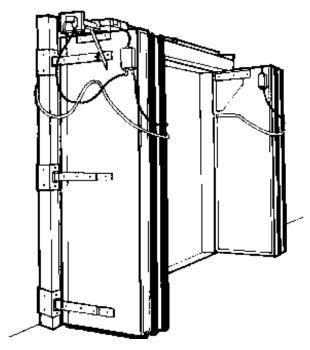


Figure 21: Bi-Folding Door.



Figure 22: High Speed Roll-Up Fabric Door.

Source: (Becker and Fricke 2005)

4.9 Lighting

Lighting affects the electricity consumption of a refrigerated storage facility in two ways. First, lighting requires electric power to operate and secondly, electric power is required by the refrigeration system to remove the heat generated by the lighting (Prakash and Singh 2008). Thus, using more efficient lighting reduces both the electric power required by the lighting and the refrigeration system.

4.9.1 Warehouse Lighting Best Practices

Wilcox et al (2007) summarize the best practices for energy efficient warehouse lighting as follows:

- Minimize connected lighting load.
- Select efficient fixtures that focus foot-candles where employees need to see.
- Use efficient fluorescent, pulse start-metal halide, or high pressure sodium lighting.
- Install occupancy controls for automatic dimming or on/off control.
- Use time clocks on lighting circuits in areas with consistent schedules.
- In warehouses that still have incandescent or mercury vapor lighting, switching to a more efficient alternative is very often cost-effective.

Beyond the reduction of energy usage, Wilcox et al (2007) also identify two additional benefits that result from following the best practices for warehouse lighting:

- Fluorescent and pulse-start metal halide lighting provide good color rendering and better lamp lumen maintenance.
- Efficient lighting improves safety and labor efficiency.

4.9.2 Metal Halide / High-Pressure Sodium Lighting Systems

In most warehouses and cold stores, vapor discharge lamps such as metal halide (MH) or high pressure sodium lamps (HPS), as shown in Figure 23, are used to provide high bay lighting. These lights are usually rated 360W for the globe and 40W for the control gear. The 400W required to produce the light puts 400W of heat into the environment. This heat has to be removed by the refrigeration system. Apart from the fact that these lamps use 75 percent more electricity than light emitting diode (LED) lamps, a major disadvantage of this type of light is the 10 minute warming up time after loss of power. The average life of a MH lamp is 15,000 hours and that of an HPS lamp is 22,000 hours. The 360W MH and HPS luminaries are very efficient sources of light, providing 100 lumens/watt or 36,000 lumens.

Using efficient lighting in refrigerated spaces reduces the refrigeration load (Wilcox et al. 2007). Most existing refrigerated warehouses and distribution centers use metal halide or high-pressure sodium fixtures. There are now aisle-style fixtures that put out a narrow rectangular light pattern, allowing fixture spacing to be increased. By selecting high-efficiency fixtures and modern pulse-start metal halide ballasts, the total connected load can be reduced.



Figure 23: High Pressure Sodium High Bay Light.

Source (RWTA 2009)

High intensity discharge (HID) fixtures designed for metal halide lamps are often categorized as high-bay or low-bay distribution (Northest Energy Efficiency Partnerships 2000). The light distribution of high-bay fixtures is usually symmetrical, and is often adjustable to produce a narrow to medium wide light pattern (44 - 60 degrees) with spacing criteria values of 1.0 or less. This light distribution is meant to concentrate light on horizontal work surfaces from lofty mounting heights of 25 feet or more.

Aisle-lighting fixtures are designed with an asymmetric light distribution to specifically solve the unique requirements of this kind of area. Perpendicular to the stacks, the light distribution is high and broad to light the stored material top to bottom. Parallel to the aisle, light distribution is narrow so that workers are not disturbed by high angle light as they travel down the aisles.

In addition, both metal halide and high-pressure sodium fixtures can be equipped with bi-level controls that allow the fixture to immediately transition to and from a low-level light output and power condition (Wilcox et al. 2007). Motion detectors can be installed in one or more zones within an aisle, or each fixture can have its own motion detector. Time clocks are another option that can be effective in areas with consistent schedules.

In storage areas, metal halide lighting can be installed or retrofit with bi-level lighting. A single fixture or group of fixtures can be controlled by a motion detector. When no activity is seen for several minutes, the fixture dims. A typical 400 watt metal halide fixture may draw 465 Watts during normal operation and only 180 watts to 200 watts during dimmed operation. When motion is detected, the fixture immediately increases light output without the delay common to the initial start-up of metal halide or other high-intensity discharge fixtures (Wilcox 2001).

4.9.3 Fluorescent Lighting Systems

Fluorescent tubes, especially in the compact form, as shown in Figure 24, have become the energy efficient light source of choice. Offering 40 to 80 lumens per watt, they are indeed much more efficient than halogen or incandescent lamps, as well as longer lasting. Although

fluorescent lights have lifetimes of 10,000 to 20,000 hours, this is less than a third of the life of an LED fitting. Florescent lamps suffer from reduced output and life expectancy when operating at low temperatures. The lifetimes of the tubes are also reduced with frequent switching. The tubes are fragile and hard to protect against accident or vandalism. Once damaged, the poisonous phosphor layer on the inside of the glass is exposed, making glass cuts particularly dangerous. The latest LEDs are at least as efficient, matching or exceeding the 70 lumens per watt typically achieved, allowing for power conversion and/or inverter losses.



Figure 24: Compact Fluorescent Light.

Source (RWTA 2009)

Increasingly, modern fluorescent lighting systems are being considered for refrigerated warehouse applications (Wilcox et al. 2007). Both T8 and the emerging T5 lamps have high color-rendering qualities. They can be applied at cooler (32°F) and freezer (0°F) temperatures provided they are integrated into enclosed fixtures. Insulated or heated fixtures may be required in freezer applications. Often, one of the lamps within a fixture is left on for safety, and the rest can be turned off with motion detectors.

Both twin-tube and linear fluorescent fixtures equivalent to HID are available; typically these have better color rendering properties than HID fixtures (Northest Energy Efficiency Partnerships 2000).

4.9.4 Halogen Lighting Systems

Halogen lights have been used for cold store lighting, but their comparative inefficiency and relatively short life makes them costly to the operator. Typical life is 2,000 to 4,000 hours for halogen, as compared to 10,000 to 20,000 hours for fluorescent tubes. For LEDs, a typical life is 50,000 to 100,000 hours, eliminating the need to replace light globes as part of the regular maintenance. Reduced energy consumption is another benefit. Halogen lamps offer around 20 lumens per watt, generating the 'waste' energy output as heat and infra-red radiation. LEDs have an efficiency of 70 to 100 lumens per watt. The lighting heat load on the refrigeration system leads to additional energy costs (RWTA 2009).

4.9.5 Light Emitting Diodes

Light emitting diodes (LEDs) bring several advantages including high efficiency and durability, and, with superior life over other lamp sources, their required maintenance is greatly reduced. This translates into energy savings, maintenance savings and an overall reduction in cost of ownership over the product's lifetime. LED fixtures also have an environmental advantage in that they contain no mercury, last longer, produce less waste and they are made from fully recyclable materials.

Oxford Cold Storage Company's new 14,500 pallet freezer store in Laverton, North Victoria, Australia, uses energy efficient solid state light emitting diode (LED) high-bay lights and saves 58 percent of the lighting operating costs (RWTA 2009). After calculating the reduction in refrigeration load, the savings are \$43,000 and result in a saving of 635 tons of CO₂ per year.

The required light level in the high rise store was calculated to be 160 Lux at 1 meter from the floor. The design called for 169 metal halide (MH) or high pressure sodium (HPS) lights with a 400 W heat load each. These were replaced with 257 LED lights with 110 W heat load per lamp. The estimated payback time for the additional cost and additional number of lights is 1.74 years. After four years the lights will have paid for themselves in electricity savings (RWTA 2009).

Light emitting diodes (LEDs) were originally developed for use as indicator lights. The light power emitted by LEDs has grown steadily over the years and at the same time efficiency has improved. LEDs are a solid state technology based on semiconductors, and their performance is affected by a range of factors, the most critical being the temperature of the junction. The low temperatures in chillers and freezers helps to maintain a low junction temperature and, as a result, these lights will theoretically have a life well in excess of the 50,000 hours claimed by the chip manufacturers. Lasting up to five times as long as fluorescent tubes, three times as long as vapor discharge lamps and using one-third the energy of other lamps, the return on investment (ROI) in terms of reduced maintenance and energy cost justifies their installation in new and refurbished buildings. Highly robust and especially low power consumption means that they can operate from a battery source or from solar panels.

The 110 W single chip LED lights installed at Oxford Cold Storage have 91 percent efficiency, producing 10,000 lumens of light and 110W of heat. So how does the LED light provide the same level of illumination as the discharge lamps? The number of LED lights installed was 50 percent more than what would have been required had Oxford used discharge lamps. With the latest 120W and 140W single chip LED lights the number of additional units required should substantially reduce and come close to one for one. Discharge lamps produce light in a spherical direction whereas the single chip LED light is a flat, unidirectional 4.0 cm² light source (RWTA 2009).

Cheaper vapor discharge lamps using standard reflectors have a low light output. More expensive reflectors can increase the luminaries' efficiency by more efficiently dispersing the scattered rays of light emitted from a spherical globe. Oxford's experience with discharge lamps was that most of the light was near the ceiling and near the top of the racking system.

The useable light reaching the floor was a combination of reflected light from the ceiling and direct light from the lamp.

Single chip LED light fixtures (Figure 25) use a flat unidirectional 4.0 cm² light source as shown in Figure 26. The LED chip is located at the top end of the reflector and, with the correct choice of reflector, it is able to achieve 180 Lux at 1 meter from the floor with the lights spaced at 5 meters and at a height of 11 meters. The light produced does not bounce around the inside of the reflector loosing intensity but it is directed vertically towards the floor of the aisle. The area above the racking remains relatively dark as all the light is used where it is required.



Figure 25: Single LED High Bay Light.

Source (RWTA 2009)

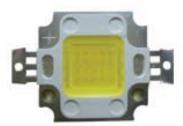


Figure 26: Single Chip LED diode.

Source (RWTA 2009)

4.9.6 Safety Lighting

Safety lighting (sometimes called "emergency lighting") allows people to enter a space, occupy it, and move through or exit it without endangering their physical wellbeing (LANL 2002). Building codes require that potential hazards, circulation areas, entrances, and exits must be illuminated. Guidelines for designing safety lighting systems are:

- Select low-energy safety lighting fixtures. Use high-efficacy lamps in efficient fixtures and provide safety lighting only to the required lighting level.
- Operate safety lighting only when needed. Use occupancy sensors and photo sensors to control safety lighting.

 Place all safety lighting on separate lighting circuits. Separating circuits leads to the ability to turn off the safety lighting when it is not needed.

4.10 Venting

The change in pressure within a refrigerated storage facility due to a change in temperature and/or humidity may cause catastrophic damage to the insulated structure if pressure equalization devices are not fitted to the cold storage rooms. Substantial pressure differentials between the inside and outside of an insulated envelope can be caused by evaporator defrosting, influx of warm product, or rapid change of barometric pressure. If vents are not fitted, movement of insulated panels, disruption of vapor retarders, and structural damage may occur.

The ideal gas law may be used to quantify the effect of air temperature on air pressure within the facility. Considering the air within a refrigerated space to behave as an ideal gas, the following relationship between temperature and pressure at two different thermodynamic states may be written:

$$\frac{P_1 V_1}{P_2 V_2} = \frac{m_1 R_1 T_1}{m_2 R_2 T_2} \tag{3}$$

where *P* is pressure, *V* is volume, *m* is mass, *R* is the ideal gas constant for air, and *T* is absolute temperature. The subscripts refer to two different thermodynamics states, designated as 1 and 2. It can be assumed that the mass of air and volume of air in the refrigerated storage facility remain constant during a change of state. Thus, the ideal gas law reduces to:

$$\frac{P_1}{P_2} = \frac{T_1}{T_2} \tag{4}$$

Hence, from the equation above, it can be seen that if the air temperature within the refrigerated space increases, the pressure will also increase. Conversely, if the air temperature within the refrigerated space decreases, the pressure will also decrease. Therefore, pressure equalization devices, or vents, are required to prevent damage to the insulated structure due to large pressure differentials between the inside and outside of the refrigerated space.

A typical vent, shown in Figure 27, consists of two side-by-side openings with hinged vent doors. One vent door swings inward, allowing air inflow, and the other vent door swings outward for exhaust. In the case of sub-freezing refrigerated spaces, the vent doors should be fitted with trace heating to prevent the formation of frost around the vent door seals.

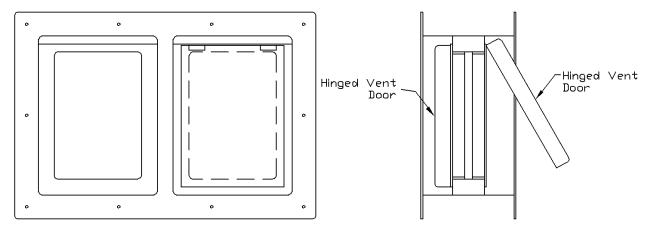


Figure 27: Pressure Equalization Vent.

Source: (Becker and Fricke 2005)

In IP units, the following equation may be used to determine the required vent area, A (ft²), of a refrigerated space (IACSC 1999b):

$$A = \frac{3.42 \times 10^{-3} Q}{\sqrt{\left(\frac{5}{9}T + 255\right)\Delta P}}$$
(5)

where Q is the rate of heat removal from the refrigerated space (Btu/hr), T is the temperature of the refrigerated space (°F), and ΔP is the design pressure differential between the interior and exterior of the insulated envelope (in. Hg). A typical value of ΔP is 0.04 in. Hg (IACSC 1999b).

In SI units, the following equation may be used to determine the required vent area, A (m^2), of a refrigerated space (IACSC 1999b):

$$A = \frac{0.063Q}{\sqrt{(T+273)\Delta P}}\tag{6}$$

where Q is the rate of heat removal from the refrigerated space (kW), T is the temperature of the refrigerated space (°C), and ΔP is the design pressure differential between the interior and exterior of the insulated envelope (Pa). A typical value of ΔP is 125 Pa (IACSC 1999b).

It is recommended that at least two vents should be installed in the refrigerated space so that the required pressure equalizing vent area is available even if any one of the vents is inoperative (IACSC 1999b). Also, vents should not be placed on opposing walls since outside wind conditions could create a pressure differential between the opposing walls, causing the vents to open unnecessarily.

4.11 Sustainable and Green Building Materials

The use of durable, attractive, and environmentally responsible building materials is a key element of any high-performance building effort (LANL 2002). Many construction materials have significant environmental impacts from pollutant releases, habitat destruction, and

depletion of natural resources. This can occur during extraction and acquisition of raw materials, production and manufacturing processes, and transportation. In addition, some construction materials can harm human health by exposing workers and building occupants to toxic and hazardous substances (DOE 2001).

Selecting environmentally attractive materials with reduced environmental impacts is primarily achieved through the practice of resource conservation and selection of non-toxic materials (LANL 2002). Environmentally preferable building materials have a reduced adverse effect on human health and the environment when compared with competing products for the same application. The selection of environmentally preferable construction materials should always be based on functional performance, environmental performance, and economic costs. First costs and life cycle costs for building materials must be taken into consideration to ensure a balance between functional and environmental performance.

4.11.1 Interior/Exterior Paints

Latex paints are available with recycled content. Reprocessed latex paints in white, off-white, and pastel colors are available with up to 20 percent recycled content. Reprocessed latex paints in gray, brown, earth tones, and other dark colors are available with up to 99 percent recycled content. Consolidated latex paint (no color designation) composed of 100 percent recycled content is available for use as an undercoat or for exterior applications where color is not of concern.

Paint is a potential contributor to poor indoor air quality (IAQ). Regardless of the types of paints used, volatile organic compound (VOC) emissions from paints should be minimized. Green Seal (GS), an independent nonprofit organization that certifies products following the ISO 14024 environmental labeling standards, has developed a standard (GS-11: Paints) to limit VOC emissions and prohibit the use of specific toxic chemicals in paints. Interior and exterior paints used should comply with the GS standard. Although not all paints meet the GS standard, all major paint manufacturers produce GS-compliant paints (though very few of them are certified by Green Seal). There is little or no cost increase associated with GS compliant paints. Recycled paints are typically less expensive than new "virgin" paints.

4.11.2 Sealants and Adhesives

IAQ considerations are the most important sustainability characteristics associated with sealants and adhesives. These products can contain toxic chemicals that are released during construction as well as during building occupancy. Due to air quality laws enacted in the state of California, all major sealant and adhesive manufacturers now offer products that limit VOC emissions and prohibit the use of specific toxic chemicals. Green Seal has also developed a standard (GS-36: Commercial Adhesives) to limit VOC emissions and prohibit the use of specific toxic chemicals. California and/or GS-compliant adhesives should be required for construction.

No-VOC and low-VOC sealants and adhesives are readily available and are becoming the industry standard. As a result, such non-emitting or low-emitting sealants and adhesives can be used at no additional cost.

4.11.3 Steel

All steel manufactured in the United States contains recycled content. Recycled content varies based on the type of furnace used for processing. Steel from a Basic Oxygen Furnace (BOF) contains approximately 30 percent recycled content on average. Steel from an Electric Arc Furnace (EAF) contains nearly 100 percent recycled content. Structural shapes (such as I-beams) are typically manufactured using the EAF, while historically, other steel products such as plates, sheets, and tubing components have been manufactured using the BOF. As EAF plants get more sophisticated, however, more and more profiles are available from those facilities.

No additional costs are associated with recycled-content steel products due to the inherent recycling in all U.S. steel manufacturing processes. Although some products manufactured using foreign steel may actually be less expensive, the recycled content in foreign steel may be unknown. Foreign steel products are not recommended due to the environmental cost associated with energy and natural resources expended for transportation.

At a minimum, steel surfaces generally require a protective primer coat to prevent rust and corrosion. Depending on the visibility of the particular material, paint may also be applied. Such coatings have potential to degrade air quality by emitting toxic VOC's. No or low VOC paints and primers should be applied to steel surfaces when such coatings are required. In addition, application of paints and primers at the manufacturing facility is always preferable due to better process emission controls.

4.11.4 Cement/Concrete

The manufacturing of cement has significant environmental impacts, including energy consumption, natural resource depletion, and greenhouse-gas emissions. The manufacturing of cement is the most significant contributor to these emissions. The amount of cement used in concrete can be reduced by replacing a portion of the cement with coal fly ash and/or ground granulated blast furnace (GGBF) slag. The level of fly ash in concrete typically ranges from 15 to 35 percent of total cementitious material, but can reach 70 percent for use in massive walls, girders, road bases, and dams. The level of GGBF slag usually ranges from 25 to 50 percent. The amount of fly ash and/or GGBF slag used in cement or concrete constitutes the recycled content. Cement and concrete containing such additives should be readily available at no increased cost. Fly ash often contains elevated concentrations of natural radioisotopes. Radioanalytic laboratories should evaluate the potential impact of the residual radioactivity.

An additional environmentally preferable feature of concrete is its potential to contribute to energy efficiency by providing thermal mass to a building envelope that slows heat transfer.

4.11.5 Insulation

Insulation is a critical component of an energy-efficient building. Energy (or thermal) performance associated with insulation is based on the thickness needed to achieve a specified or desired thermal resistance (such as R-19 walls and R-30 roof). In addition to the energy (or thermal) characteristics of insulation, recycled content and toxicity (to both human health and the environment) of insulation must be considered. Although some manufacturers now offer formaldehyde-free fiberglass insulation, phenol formaldehyde is widely used to bond the fibers

in fiberglass batts. In addition to formaldehyde concerns, airborne fiberglass particulates are considered an inhalation irritant. Such fibers can become airborne when installing insulation, and can be distributed throughout a building. However, insulation manufacturers can control the release of particulate fibers by encapsulating the batts in a thin plastic film.

The optimal amount of insulation in the building envelope should be determined based on computer models of the building's overall thermal performance. Insulation containing recycled-content material is readily available from all major insulation manufacturers at no increased cost. Formaldehyde-free fiberglass insulation, however, is relatively new, and not universally available.

4.11.6 Brick/Concrete Masonry Units (CMU)

Brick provides thermal mass that adds to energy efficiency by slowing heat transfer through the wall. Brick is also very durable, requiring essentially no maintenance because it never needs to be painted and never rots, fades, warps, burns, dents, tears, or becomes brittle. Salvaged brick may be available depending on local vendor supplies. New brick can be matched to salvaged brick as necessary. Although brick containing recycled content has not been identified, locally manufactured brick is available.

Brick wall construction is generally less expensive (both first cost and life cycle cost) than precast concrete panel, metal panel, and exterior insulation finish system walls. Salvaged brick can actually cost more than new brick due to the labor required to refurbish used brick for resale. Concrete masonry units (CMU) or concrete blocks are less expensive than brick and may be available with recycled content. CMUs with finished faces can provide both the structure and either the interior or exterior surface of a wall, thereby replacing whole layers of additional material. For energy efficiency and comfort, it is best to locate the CMU on the inside and insulation on the outside of the wall, for example, CMU with an exterior finish insulating system (EFIS).

4.11.7 Roofing

Dark, non-reflective roofing surfaces create heat island effects by absorbing energy from the sun and radiating it as heat. This "black body" effect causes ambient temperatures to rise, which increases cooling requirements. A roof system with light colors can reflect heat instead of absorbing it, reducing energy use. Depending on the roofing system selected, there is potential for roofing materials to contain recycled content and low-emitting materials.

4.11.8 Doors

Exterior doors (and frames) should be constructed of recycled-content steel and contain insulating core material that does not contribute to ozone depletion. Rigid foam plastics and fiberglass are typically used as insulating cores. In the case of foam plastics, expanded polystyrene (EPS) is preferable to extruded polystyrene and polyurethane. Fiberglass core materials should also contain recycled content. Finishes on steel doors should be applied at the factory (where process emission controls are in place) and consist of a no- or low-VOC paint that is cured (or baked) to eliminate VOC emissions after installation. Weather-stripping along the top, jambs, and bottom sweeps will minimize air infiltration around exterior doors.

4.11.9 Insulating Concrete Forms (ICF)

The thermal efficiency of insulating concrete form (ICF) construction is attributable to the insulation properties of the form material, temperature stability from the thermal mass of concrete, and reduced air infiltration. ICF walls can have thermal resistance (or R-value) of approximately R-15. Both the insulation material of the forms and the concrete used in ICF construction could contain recycled content. The potential for toxic emissions from ICF walls is low based on the materials used for construction. Expanded polystyrene is the most common insulation material used in ICF construction, and along with concrete, these materials generally have no emissions.

The relative cost for ICF construction is nearly equivalent to poured concrete or concrete block construction. ICF construction is marginally more expensive when compared to wood or steel-frame construction. However, the energy savings resulting from ICF construction may result in a lower overall life cycle cost compared to conventional wall construction techniques.

4.11.10 Structural Insulated Panels (SIP)

Facing materials in Structural Insulated Panel (SIP) construction are commonly metal sheets, drywall or structural wood sheathing (such as plywood and oriented strand board). Similar to ICFs, the foam insulation used as core center should be EPS (which is most commonly used) to eliminate potential contributions to ozone depletion. Sheathing and adhesives used in the construction of SIPs have the potential to release toxic emissions, such as formaldehyde and VOCs.

The cost for SIP construction is equivalent to poured concrete or concrete block, and marginally higher than conventional frame and insulation package construction. However, life cycle considerations indicate reduced overall costs due to the substantially increased energy efficiency over conventional construction techniques.

4.11.11 Permeable Paving

Permeable (or porous) paving can be used to control surface water runoff by allowing stormwater to infiltrate the soil and return to the watershed (LANL 2002). Permeable paving includes methods for using porous materials in locations that would otherwise be covered with impermeable materials (parking areas, walkways, and patio areas). These methods and materials include:

- Permeable pavers Paving stones placed in an interlocking fashion over pedestrian surfaces (such as walkways and patios).
- Gravel/crusher fines Loose aggregate material used to cover pedestrian surfaces.
- Open cell pavers Concrete or plastic grids with voids that are filled with a reinforced vegetative turf or an aggregate material (sand, gravel, crusher fines). These are applicable to limited-vehicle-use areas.
- Porous asphalt (bituminous concrete) A porous asphalt layer constructed with "open-graded" aggregate (small fines removed), which leaves voids between the large particles unfilled by smaller fine particles. An open-graded stone base holds water until it filters through into the underlying soil. This is applicable to general-vehicle-use areas.

• Porous concrete – A concrete mix that does not contain fine aggregate but does contain special additives for strength.

Permeable paving is not intended to replace standard impervious paving, but to limit the use of impermeable paving to heavy traffic areas. The availability of recycled content, salvaged materials, and locally manufactured products depends on the specific techniques implemented. Impacts from snow removal and control (salting) may affect durability. Permeable paving surfaces generally cost more than conventional impervious surfaces. However, life cycle savings include reduced cost for stormwater management facilities and equipment and reduced operation and maintenance for infrastructure repairs. Permeable paving can potentially eliminate the need for stormwater collection drains, subsurface piping, and discharge structures.

4.12 Managing Construction Waste

Construction activities generate significant quantities of solid waste. The primary intent of sustainable construction waste management practices is to conserve resources by minimizing the amount of material disposed of in landfills. Always conduct construction waste management on the basis of the three- "R's" hierarchy: reduce, reuse, and recycle (LANL 2002).

On many construction projects, recyclable materials such as wood, concrete and masonry, metals, and drywall make up as much as 75 percent of the total waste stream, presenting opportunities for significant waste diversion (DOE 2001). Construction waste management takes advantage of opportunities for source reduction, materials reuse, and waste recycling. Source reduction is most relevant to new construction and large renovation projects and involves reduced "waste factors" on materials ordering, tighter contract language assigning waste management responsibilities among trade contractors, and value-engineering of building design and components. During renovation and demolition, building components that still have functional value can be reemployed on the current project, stored for use on a future project, or sold on the ever-growing salvage market. And recycling of building materials can be accomplished whenever sufficient quantities can be collected and markets are readily available.

CHAPTER 5: Load Calculations

In order to properly size the refrigeration equipment of a cold store, it is necessary to first perform accurate heat load calculations. The major contributors to the overall heat load are as follows (Stoecker 1998; Krack Corporation 1977; McQuiston and Spitler 1992; U.S. Navy 1986).

- Heat transmission through the roof, floor, and walls.
- Solar heat gain through roof and walls.
- Infiltration through open doorways and through cracks around closed doors.
- Internal loads from people, motors and lights.
- Product load.
- Defrost load.

5.1 Peak Load Calculations vs. Hourly Calculations

Currently, industrial refrigeration systems are typically designed based upon the anticipated peak load with little or no consideration for load variation due to time of day, weekends, holidays, seasons of the year, and processing and movement of product.

Effective green design and operation of a refrigerated facility requires accurate calculation of the seasonal, hour-by-hour refrigeration load experienced by the facility, including the effects of the diurnal cycle as well as weekends and holidays. Product movement and processing also significantly affect the refrigeration load. Effective green design of refrigeration equipment used in these facilities requires accurate estimation of the time-dependent cooling and/or freezing loads, both sensible and latent, of the stored food items, as well as the sensible heat load which is transmitted through the walls, roof and floor of the storage facility. In addition, the sensible and latent heat loads imposed by openings in the refrigerated storage facility, such as doors and loading docks, must be considered. These load calculations should be based upon accurate, comprehensive local weather data.

This type of load calculation procedure will facilitate proper incremental sizing of compressors, evaporators and condensers to track variations in the refrigeration load while still satisfying peak load, thus enabling maximum efficiency. The use of a computer-based energy management system to control the incremental refrigeration equipment so as to meet the varying load will also result in significant energy savings.

Steady-state heat loss and gain calculations have commonly been used to determine peak loads and equipment sizes, but they give only a brief snapshot of the thermal performance under design load conditions in the summer and winter. They do not indicate the overall energy performance of the building, nor do they adequately treat daylighting, solar loads, and thermal capacitance effects. Only through dynamic hour-by-hour (or shorter time-step) computer simulations over a typical climate year will the complete picture of energy use, energy cost, and

peak load be revealed. Computer modeling early in the design process can pinpoint areas of particular concern and highlight areas of potentially significant energy savings (LANL 2002).

5.1.1 Total Heat Load

The total heat load, Q_{Total} (Btu hr⁻¹ or kW), is calculated as the sum of the transmission, infiltration, internal (people, motors and lighting) and product loads(Becker and Fricke 2005). All the loads are summed and no consideration is given to the probability that all the loads may not occur at the same time. Thus, load diversity is not taken into consideration.

The total heat load is given as:

$$Q_{Total} = Q_{Transmission} + Q_{Infiltration} + Q_{People} + Q_{Motor} + Q_{Lighting} + Q_{Product}$$
(7)

After the total load is calculated it is recommended to apply a factor of safety, F_s , typically 10 percent, to account for defrost heat and other miscellaneous sources of heat, as well as possible discrepancies between the design criteria and actual operation. The magnitude of this factor of safety should be selected in consultation with the facility owner.

In addition, one must consider variations in the refrigeration load due to the diurnal cycle, weekend operations and seasonal effects as well as product cool down periods.

Sizing the refrigeration equipment according to this total heat load is the most conservative approach, but it may result in oversized refrigerating equipment. The reason for such overestimates is that all the component loads do not occur at the same time of the day nor do they occur at their maximum value.

5.1.2 Hour-by-Hour Calculations and Diversity

If the design component load data are reasonably well defined in terms of both magnitude and occurrence, then the hour-by-hour calculation method may be used to calculate the heat load, and thus the diversity of operation is taken into consideration. The heat load calculated using the hour-by-hour method may be less than the total load, resulting in a reduction of required refrigeration capacity.

Alternatively, a diversity factor, based upon an analysis of the magnitude and occurrence of the design component loads, may be applied to the total heat load. Typically, the diversity factor has a value between 0.6 and 1.0.

5.1.3 Compressor-Side Refrigeration Tonnage

The compressor-side refrigeration tonnage, $T_{R, Compressor}$, used to select compressors, condensers and other machine room equipment is given as:

$$T_{R,Compressor} = \frac{F_D (1 + F_s) Q_{Total}}{12000 \text{ Btu} \cdot \text{hr}^{-1} \cdot \text{ton}^{-1}}$$
(8)

where Q_{Total} is the total heat load (Btu hr⁻¹), F_s is the factor of safety (0.10) and F_D is the diversity factor (0.6 to 1.0).

5.1.4 Evaporator-Side Refrigeration Tonnage

The evaporator-side refrigeration tonnage, $T_{R, Evaporator}$, used to select fan-coil evaporator units, is greater than the compressor-side refrigeration tonnage, $T_{R, Compressor}$. The evaporator-side refrigeration tonnage must be increased to account for the hours of operation lost during defrost. The evaporator-side refrigeration tonnage, $T_{R, Evaporator}$, is then given as:

$$T_{R,Evaporator} = \frac{24}{\left(24 - t_{Defrost}\right)} \frac{F_D \left(1 + F_s\right) Q_{Total}}{12000 \text{ Btu} \cdot \text{hr}^{-1} \cdot \text{ton}^{-1}}$$
(9)

where Q_{Total} is the total heat load (Btu hr⁻¹), F_s is the factor of safety (0.1), F_D is the diversity factor (0.6 to 1.0) and $t_{Defrost}$ is the total number of hours of defrost per evaporator per day.

5.1.5 Psychrometrics

The designer of refrigerated storage facilities should pay particular attention to psychrometrics and the psychrometric processes which occur when warm, moist air encounters refrigerated air, predominately at doorways. The proper use of psychrometrics will significantly reduce the possibility of fog, frost or ice formation which may occur during the operation of the refrigerated facility.

5.2 Whole Building Energy Simulations

5.2.1 Whole Building Energy Simulations

Building energy performance simulation is a powerful tool for integrated design that enables architects, engineers, and developers to analyze in an integrated way how the form, size, orientation, and type of building systems affect overall building energy consumption (Lewis 2004). This information is vital for making informed design decisions about building systems that impact energy use, including envelope, glazing, lighting, and refrigeration. It is often the case that a few building simulation runs in the early phases of a project can lead to design solutions that, though they appear simple, significantly improve building energy performance. Although many designers are qualitatively aware of the high degree of interaction between different building systems, it is difficult, and in some cases impossible, to accurately quantify those interactions without using building simulation. Typically, many designers address such issues either by following rules of thumb, by relying on intuition, or by ignoring them altogether. By using building simulation to help make decisions, designers and developers can provide more value to the building operators who must eventually pay the utility bills, and they also can protect themselves by providing a quantitative basis for design decisions.

During the building design phase, the team must ensure that the sustainable design strategies are integrated holistically into the building design. Effectively integrating the building envelope and systems can only be accomplished by relying on building energy simulation tools to guide design decisions. Simulation results provide insight into how the building is expected to perform. Therefore, it is recommended that the RFP states that the contracted project team is required to use computer simulations throughout the design process (LANL 2002).

The thermal performance of any building entails complex interactions between the exterior environment and the internal loads that must be mediated by the building envelope and mechanical systems. The difficulty is that these various external and internal load conditions and associated utility loads are constantly changing from hour to hour and season to season. Also, the number of potential interacting design alternatives and possible trade-offs is extremely large. Computer simulations are the only practical way to predict the dynamic energy and energy cost performance for a large number of design solutions. Accurate energy code-compliant base-case computer models give the design team typical energy and energy cost profiles for a building of similar type, size, and location to the one they are about to design. The design team uses this information to develop a design concept to minimize these energy loads and energy costs from the very outset. At this stage, the design team can manipulate the building massing, zoning, siting, orientation, internal organization, and appearance of the facades without adding significantly to the cost of design

5.2.2 EnergyPlus and California Title 24

The building energy analysis tool, DOE-2, has been used by the state of California to develop its building energy efficiency standards, such as Title 24. However, DOE-2.1E is no longer being supported by its developer, Lawrence Berkeley National Laboratory (LBNL), or any other public or private entity. The USDOE has developed a new building energy analysis tool, EnergyPlus, which is intended to replace DOE-2.1E (Hong, Buhl, and Haves 2009).

However, EnergyPlus is not capable of straightforwardly modeling refrigerated warehouses (Hong, Buhl, and Haves 2009). In a study performed by LBNL and funded by the California Energy Commission, it was recommended that new features be added to EnergyPlus so that the program would be capable of modeling refrigerated warehouses (Hong, Buhl, and Haves 2009). The motivation for this recommendation is that the improved version of EnergyPlus would then be used to analyze energy efficiency measures for refrigerated warehouses. If the energy efficiency measures analyzed by EnergyPlus were found to be significant, they could be incorporated into future versions of Title 24 (Hong, Buhl, and Haves 2009).

CHAPTER 6: Refrigeration System Design

In this section, details of the major components of a refrigeration system are provided. This section includes a description of the basic refrigeration cycles and components used in refrigerated storage facilities, including discussions on evaporators, compressors, condensers, ammonia refrigeration systems and cascade refrigeration systems utilizing ammonia and CO₂. The design of efficient piping and opportunities to save energy through the application of high efficiency motors and variable speed drives for refrigeration compressors, fluid pumps, evaporator fans, and condenser fans are discussed. Since the configuration and placement of evaporators plays a large role in the operation of refrigerated storage facilities, greater detail is provided on various aspects of evaporators.

6.1 Evaporators

The evaporator is the basic component of the refrigeration system which provides the cooling (Stoecker 1998; Crawford, Mavec, and Cole 1992; IIR 1993). In industrial refrigeration applications, there are two primary types of evaporators: 'refrigerant-to-air coils' and heat exchangers. Likewise, there are two primary categories of heat exchangers: 'refrigerant-to-secondary fluid' chillers and direct contact chillers/freezers. The configuration of an evaporator depends upon the medium it is cooling. In refrigerated storage facilities, evaporators that are used to cool the air in the refrigerated space are generally tube coils with fins and fans.

Liquid chilling evaporators are usually the shell and tube type or plate and frame type. Plate and frame type heat exchangers are usually selected for new applications. The refrigerant cools a secondary fluid, commonly water, glycol, or brine. The secondary fluid is then pumped to the cooling application, for example, using chilled water to cool milk products or using a brine to freeze ice cream bars or snow crabs.

In a direct contact heat exchanger, refrigerant is used to cool or freeze a food product directly. For example, milk or juice might be cooled using a plate and frame heat exchanger or ice cream may be hardened in a scraped-surface heat exchanger. In a plate freezer, refrigerant cools a plate or surface that is directly opposite a hardening product such as cartons of ice cream or fish fillets.

Since refrigerant-to-air coils are of primary importance in refrigerated storage facilities, a detailed description of air coils will be given, followed by a brief description of liquid chiller and direct contact evaporators.

6.1.1 Refrigerant-to-Air Coil Evaporators

In finned air coils, fans draw or force air over finned tubes which contain refrigerant (Stoecker 1998; Crawford, Mavec, and Cole 1992). Refrigerant flows inside the tubes, cooling the air which passes over the finned tubes.

Tube Sizes and Materials

Common materials used for making evaporator tubes include carbon steel, copper, aluminum and stainless steel. If ammonia is used as a refrigerant, then all of the above mentioned materials may be used with the exception of copper. For smaller coils utilizing halocarbon refrigerants, 3/8 inch (9.5 mm), half-inch (12.7 mm), or 5/8 inch (15.9 mm) diameter copper or aluminum tubes can be used. For ammonia refrigeration, common tube diameters are 3/4 inch (19 mm), 7/8 inch (22 mm), and 1 inch (25 mm), depending upon the type of refrigerant feed. Direct expansion feed with any refrigerant will usually use 5/8 inch (15.9 mm) diameter or smaller tubes.

Fins and Fin Pitch

Fins provide extended heat transfer surface, or secondary surface, to the coils and improve their performance (Becker and Fricke 2005). The tubes of the coil are themselves the most efficient heat transfer surface; however, using only the primary surface provided by the tubes becomes very expensive and results in extremely large coils. Thus, it is better to use fins to provide extended heat transfer surface area. The fins are usually formed from a continuous sheet of metal with holes punched to create a collar. The refrigerant tubes are placed through the holes in the sheet and the flat sheets are aligned in succession with proper spacing, provided by the collar, to form the fins. The most common fin materials include steel, copper, aluminum and stainless steel.

Fin spacing, or fin pitch, which is the number of fins per inch of tube length, varies depending upon the conditions of the room. In high-frost areas, the fins are spaced farther apart or have different pitches on successive tubes which provides for greater time between defrost cycles. For higher temperatures, a high fin pitch is used so that the coil is smaller. ASHRAE (2010a)recommends 4 to 6 fins per inch (2 to 3 fins per cm) for rooms with coil temperatures above 32°F (0°C) and for all other conditions, fin pitch should be from 3 to 4 fins per inch (1 to 2 fins per cm). Fin spacing is often varied from one tube row to another where very low air temperatures are used. When defrosting is not a concern, fins are often manufactured in a corrugated form in order to enhance air turbulence and heat transfer. Flat fin surfaces are used in low temperature freezing applications.

Tube and Fin Materials for Various Refrigerants

The most common combinations of tubes, fins and refrigerants are as follows:

- Copper tube and aluminum fin.
 - -Halocarbons.
 - -Glycol/ water.
- Steel tube and steel fin, hot-dip galvanized after fabrication.
 - -Ammonia.
 - -Halocarbons.
 - -Calcium chloride.
 - -Glycol/water.

- Aluminum tube and aluminum fin.
 - -Ammonia.
 - -Glycol/water.
 - -Halocarbons.
- Copper tube and copper fin.
 - -Halocarbons.
 - -Glycol/water.
- Stainless steel tube and stainless steel fin.
 - -Ammonia.
 - -Halocarbons.
 - -Glycol/Water.

Finned Air Coil Construction

Proper bonding between the fin and tube is required for maximum heat transfer. If there is no bonding between the fin and tube, heat transfer will be reduced due to air gaps between the fin and tube. One method for providing a good bonding between the fin and tube is to galvanize the coil. This is done by dipping the coil in molten zinc. In addition, the zinc provides a protective surface against corrosion. Other methods of bonding a fin to a tube include expanding the tube into the collar on the fin, pressing the fin on to the tube, or in case of a spiral fin coil, the fin can be tension wound onto the tube.

Tube arrangements are generally either parallel (square) or staggered (triangular). A parallel tube coil will have the least airflow resistance since the air flows through the coil in an uninterrupted manner. A staggered tube coil, shown in Figure 28, will have more air flow resistance but in general, will have a slightly higher heat transfer capacity.

Other components of evaporator coils include tube sheets and end bends. Tube sheets are the heavier portions at each end of the coil, which are used to hold the coil together and to provide mounting and handling of the coil. The tube sheets contain holes through which the tubes pass. End bends are U-shaped tubes or pipes at the ends of coils used to join the tubes together to form a complete circuit.

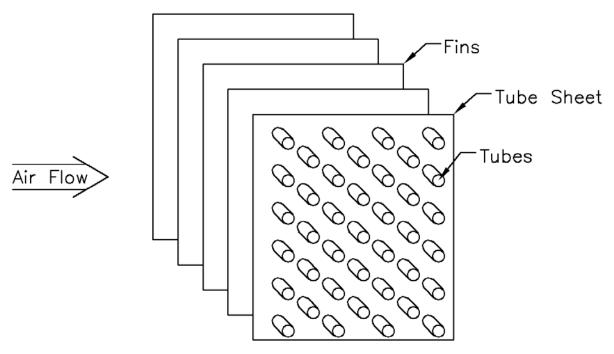


Figure 28: Staggered Tube Coil Arrangement.

Source: (Becker and Fricke 2005)

A sound evaporator coil design must take into account the tube-side pressure drops and fluid velocities. Also, an efficient evaporator design must address the tube arrangement and number of fluid feeds (circuits) within a specific fin area.

Depending upon the technique used to feed the refrigerant to the coils, finned air coils can be classified as follows:

- Direct expansion evaporators.
- Flooded evaporators.
- Liquid overfeed evaporators.

6.1.2 Direct Expansion Evaporators

In a direct expansion finned air coil, liquid refrigerant enters an expansion valve prior to entering the evaporator and the refrigerant exits the evaporator as a vapor, as shown in Figure 29 (Stoecker 1998; Crawford, Mavec, and Cole 1992). Typically, the vapor leaving the evaporator is superheated from 7°F to 12°F (4°C to 7°C). A temperature sensor at the evaporator outlet provides control for the opening or closing of the expansion valve. This type of temperature controlled expansion valve is commonly known as a superheat-controlled valve, a thermo-valve, a thermostatic expansion valve or a TXV. The direct expansion evaporator is not as effective for low temperature applications, since the evaporator surface must be oversized to accommodate the ineffective superheating of the refrigerant. On small to mid-sized systems with halocarbon refrigerants, direct expansion evaporators are used throughout for low and medium temperature applications. For ammonia refrigeration systems, direct expansion evaporators can be used down to 10°F (-12°C) for applications where a reduction in ammonia charge may be required or advantageous.

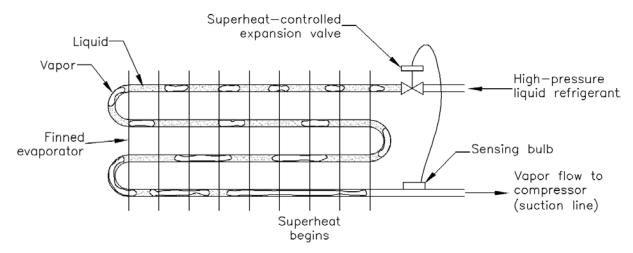


Figure 29: Direct Expansion Evaporator.

Source: (Becker and Fricke 2005)

6.1.3 Flooded Evaporators

In a flooded evaporator, shown in Figure 30, more refrigerant is circulated through the evaporator than that which evaporates (Stoecker 1998; Crawford, Mavec, and Cole 1992). Thus, all inside surfaces of the evaporator are wetted with liquid refrigerant, providing an effective exchange of energy between the refrigerant inside the evaporator tube and the air flowing outside the evaporator tube. The refrigerant vapor exits from the evaporator into a surge tank and then flows to the suction line. A level control valve is used to add liquid refrigerant to the evaporator in order to replace the amount which has vaporized. The difference in static pressure between the liquid leg and the mixture of vapor and liquid in the evaporator tubes determines the refrigerant flow. For proper refrigerant circulation, it is recommended that the surge tank be mounted at least 12 inches (0.3 m) above the top of the evaporator coils.

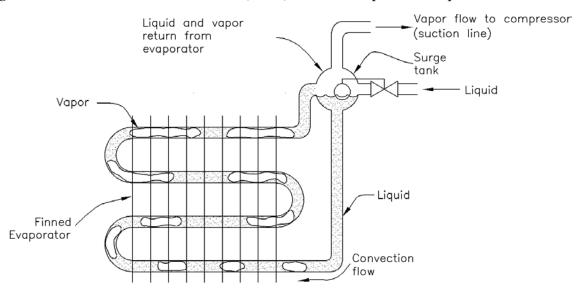


Figure 30: Flooded Evaporator with Gravity Circulation.

Source: (Becker and Fricke 2005)

The advantages of flooded evaporators as compared to direct expansion evaporators include the following:

- The evaporator surfaces are used more effectively because they are completely wetted. Thus, there is good heat transfer.
- Distributing refrigerant to parallel circuit evaporators is easier.
- Saturated vapor enters the suction line to the compressor.

However, flooded evaporators have a higher initial cost than direct expansion evaporators. In addition, more refrigerant is needed for flooded evaporators and lubricating oil tends to accumulate in flooded evaporators and must be removed periodically.

In a flooded evaporator system, a pressure regulator is located in the suction line between the surge tank and the compressor. The refrigerant pressure, and hence temperature, in the surge tank is varied by using the pressure regulator to throttle the gas returning to the compressors. When the regulator is wide open, the surge tank sees the full suction of the compressors and the refrigerant temperature and pressure, in the coil is lowest, thus maximizing capacity. As the regulator closes, the pressure rises in the coil, with a commensurate increase in boiling temperature. This decreases the temperature difference between the refrigerant and the entering air, resulting in a decreased refrigerating capacity (Wilcox et al. 2007).

6.1.4 Liquid Overfeed (Recirculation) Evaporators

In a liquid overfeed system, shown in Figure 31, liquid refrigerant is mechanically pumped to the evaporators at a rate greater than that which is evaporated (Stoecker 1998; Crawford, Mavec, and Cole 1992). The rate of flow is metered by a hand expansion valve to provide the coils with about three to four times more liquid then is boiled in the process of removing heat. Hence, the refrigerant returning from the coil is about three-fourths liquid and one-fourth vapor by weight. The combination of liquid and vapor refrigerant exits the evaporator and flows into a separating tank to separate the vapor from the liquid. The separated liquid refrigerant, and additional liquid refrigerant which replaces the vaporized refrigerant, flows to the mechanical pump for recirculation to the evaporators.

In a recirculation system, the capacity of the evaporator coil is controlled by turning the refrigerant flow on and off with a solenoid valve that is located in the liquid line between the circulating pump and the evaporator (Wilcox et al. 2007).

Liquid overfeed evaporators, as well as flooded evaporators, achieve increased heat transfer rates as compared to direct expansion evaporators. In a liquid overfeed system; the pump and separating tank contribute to a higher first cost, while the maintenance cost is usually higher for flooded evaporators. Thus, flooded coils are typically used for refrigeration systems consisting of up to three evaporators while pumped liquid (mechanical or gas pressure) overfeed evaporators are used for larger installations.

Most large cold storage facilities utilize a pumped recirculation refrigeration system. The cold storage room air temperature is controlled by a thermostat located in the storage room. This thermostat controls a solenoid valve that controls the flow of refrigerant to the evaporators. The

evaporating temperature is controlled independently by a pressure controller on the low pressure surge drum. The pressure controller controls the capacity of the compressors to maintain a specific pressure in the surge drum. Thus, the temperature of the refrigerant is equal to the saturation temperature at the surge drum pressure (BFFF 2009).

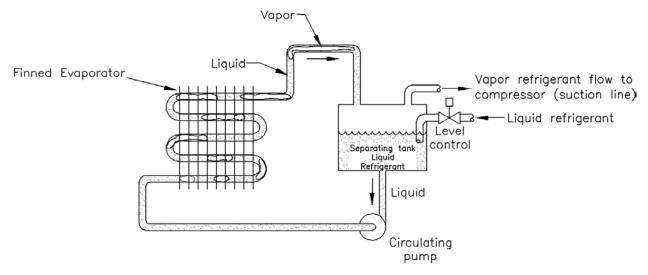


Figure 31: Liquid Recirculation Evaporator Utilizing a Mechanical Pump.

Source: (Becker and Fricke 2005)

6.1.5 Evaporator Fans

Evaporator coils can have from one to eight fans, ranging in size from less than one horsepower to 20 horsepower or more. Fans are used to increase the heat transfer capability of a coil by moving air over the coil (Stoecker 1998; Crawford, Mavec, and Cole 1992). Fans are classified as axial or centrifugal depending upon the direction of airflow through the fan's impeller.

Axial Fans

Most evaporator coils use axial fans that either push or pull the air through the coil. Axial fans consist of radial blades connected to a circular hub. Air is drawn into the fan in the axial direction and discharged in the same direction. The fan blades are directly connected to the shaft of the motor to reduce space and to cool the motor with the air stream. Axial fans are further divided into three groups: propeller, vane axial and tube axial fans (Becker and Fricke 2005).

Propeller type fans have two to four blades and can deliver air at high flow rates but at low static pressure. These fans require less power than centrifugal, vane axial or tube axial fans for a given flow capacity.

Tube axial and vane axial fans are very similar and are thus commonly called axial fans. These fans are similar to propeller fans with respect to flow direction. Tube axial and vane axial fans have four to ten blades and can deliver air at higher velocities and static pressure than propeller fans. These fans can be used with short duct lengths or in places where high flow rates are required.

Larger evaporator coils are usually equipped with cast aluminum fan blades, while smaller coils are equipped with stamped-steel propellers attached to a hub (Wilcox et al. 2007).

Centrifugal Fans

Less common are evaporator coils that use centrifugal 'squirrel-cage' fans. A centrifugal fan consists of a cylinder with blades mounted around the circumference of the cylinder parallel to the cylindrical axis. In these fans, air is drawn in along the axis of the cylinder and discharged radially through the cylinder wall. The four basic configurations for centrifugal fan blades include air-foil, backward-curved, radial, and forward curved blades. These fans operate more quietly than axial fans and deliver air at higher static pressure. However, centrifugal fans require more power than axial fans for the same pressure drop. The fan motors are connected to the fan cylinders via belts and pulleys (Becker and Fricke 2005).

Fan-Coil Configurations

An important fan characteristic is the "throw," defined as that distance from the fan at which the velocity of the air falls below 100 ft min⁻¹ (0.5 m s⁻¹).

As shown in Figure 32, there are two basic configurations for fan-coil combinations: "blow-through" and "draw-through."

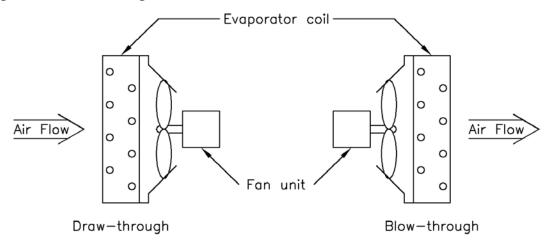


Figure 32: Draw-Through and Blow-Through Evaporator-Fan Configurations.

Source: (Becker and Fricke 2005)

The biggest advantage of the blow-through evaporator-fan configuration is that the air absorbs the heat generated by the fan motor before the air enters the coil. In the draw-through arrangement, the heat generated by the motor warms the air after the air leaves the coil. An advantage of the draw-through arrangement is it has greater throw as compared to the blow-through arrangement. Blow-through arrangements are primarily used in high humidity applications where the difference between the refrigerant and return air temperature is low.

Propeller fans are the most popular fans and they can be used for moderate throws in open spaces commonly found in storage rooms. For short ducts and penthouses, axial fans can deliver the required pressure with less energy cost than centrifugal fans and require less

maintenance. However, if high static pressure and long duct work are required, then it is recommended to use centrifugal fans (Becker and Fricke 2005).

Evaporator Fan Controls

Evaporator fans can be used to control evaporator capacity. All of the fans on an evaporator coil may be turned off periodically to disable cooling, known as 'fan cycling'. Or, a portion of the fans on an evaporator coil may be turned off during light load operation, known as 'fan shedding'. Evaporator fans may also have two speeds allowing for full or partial operation depending upon load. Furthermore, evaporator fans can be managed with variable frequency drives (VFD) to control fan speed continuously, rather than in steps to match refrigeration load (Wilcox et al. 2007).

6.1.6 Performance of Refrigerant-to-Air Coil Evaporators

The most important factors which affect the performance of coils are (Stoecker 1998; Crawford, Mavec, and Cole 1992):

- Face area of coil.
- Number of tube rows.
- Coil circuiting: bottom or top feed.
- Fin spacing.
- Air-flow rate.
- Refrigerant temperature.

Increasing the face area of the coil increases the heat transfer area and reduces the temperature of the air exiting the coil. For every additional row of tubes in a coil, there will be a reduction in air temperature and moisture content. Decreasing fin spacing increases heat transfer, resulting in lower outlet air temperature and moisture content. Increasing air-flow rate increases the heat transfer.

Surface/Air Temperature Difference

Correctly sized evaporators are necessary for efficient refrigeration system operation. A temperature difference of approximately 6°C (10.8°F) between the air exiting the evaporator and the evaporator surface indicates that there is sufficient evaporator surface to remove the heat load. Thus, the refrigeration system is operating efficiently. A higher temperature difference between the exiting air and evaporator surface indicates that the cold storage facility has been designed with insufficient evaporator surface area and the refrigeration system is operating inefficiently (BFFF 2009).

Effects of Evaporating Temperature

The evaporating temperature can strongly influence the efficiency of a refrigeration system. For a typical cold storage facility, a 1°C (1.8°F) increase in the evaporator temperature, with the condenser temperature held constant, can result in an operational cost savings of approximately 2 percent to 3 percent (BFFF 2009). Thus, for maximum energy efficiency, the evaporating

temperature within a cold storage facility should be maintained as high as possible to preserve the quality of the food during the required storage period.

The refrigeration system should be operated in such a manner as to minimize the cold room air temperature fluctuations. It is possible to operate a refrigerated storage facility such that the fluctuation in room temperature is less than $\pm 0.5^{\circ}$ C ($\pm 0.9^{\circ}$ F) (BFFF 2009). Larger variations in room air temperature result in lower average evaporator temperatures, which in turn, result in greater energy consumption.

Where climate permits, it is suggested that seasonal adjustment of evaporating temperature be employed to maximize energy efficiency. During the winter, the cooling load of a cold storage facility is less than in the summer. Thus, the suction temperature could be raised 1°C to 2°C (1.8°F to 3.6°F) in the winter to reduce energy consumption while still maintaining optimum storage temperature (BFFF 2009).

6.1.7 Placement of Refrigerant-to-Air Coil Evaporators

Air Distribution in the Storage Space

Proper air circulation is required to maintain a uniform temperature and avoid temperature stratification within a refrigerated storage facility (Becker and Fricke 2005). Air movement is necessary to remove respiratory heat and heat gained through walls, roofs and doorways. To ensure proper air circulation, evaporators may be ceiling mounted, floor mounted, or located in a penthouse above the refrigerated space. In some cases, there may be partial or full ductwork to provide the necessary air circulation. The number and location of the evaporators is dependent on the room size, configuration, refrigeration load and room temperature requirements. In addition, there should be adequate space for accessibility to the evaporators, piping and operating controls. Since the internal configuration of the storage space and the stacking arrangement are the most influential factors affecting air distribution, the air distribution system should be designed in conjunction with the internal configuration of the refrigerated storage facility and the stacking arrangement.

When product is delivered to the storage facility at a temperature measurably greater than the storage temperature, it is recommended that the product be rapidly pre-cooled to the storage temperature in a separate pre-cooling room. The pre-cooler should have a higher air circulation rate and a greater refrigeration capacity to rapidly remove field heat from freshly harvested commodities, residual heat from processing operations, and/or heat gained during transport. Since excessive air movement can increase moisture loss from the product, resulting in the loss of both mass and quality, high air velocities are undesirable after pre-cooling, unless high humidity is maintained.

Ceiling Mounted Evaporators

The number of air coils and their placement is important in achieving uniform temperatures within the refrigerated space (Stoecker 1998; Crawford, Mavec, and Cole 1992). Evaporator coils are usually suspended from the ceilings of refrigerated spaces and the coils should be positioned so that they direct the airflow down the aisles and in the same direction as

supporting beams and structural members. The airflow from coils should be parallel to the doors, as shown in Figure 33. Evaporators should not be suspended in front of doors, since the warm, moist air from outside will be drawn directly inside, or the refrigerated air will be discharged directly outside, when the door is opened, as shown in Figure 34.

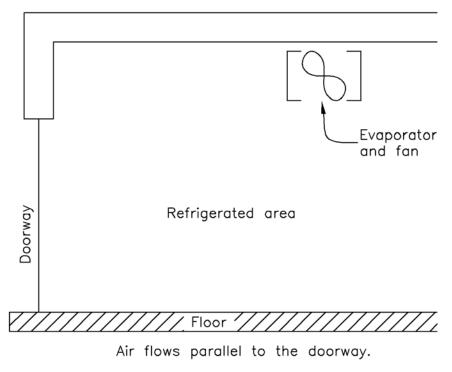


Figure 33: Correct Evaporator Location and Orientation Near a Doorway.

Source: (Becker and Fricke 2005)

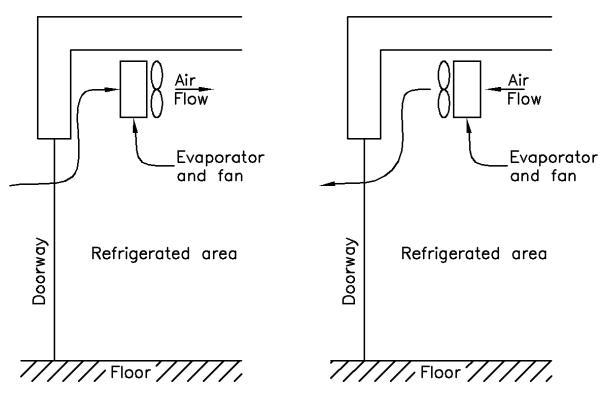


Figure 34: Incorrect Evaporator Location Near a Doorway [4]

Source: (Stoecker 1998)

Penthouse Mounted Evaporators

The penthouse system of installation is also used to mount evaporators in the cold spaces of large refrigerated storage facilities. In this technique, the evaporator coils are kept together in a penthouse, located on the roof of the facility, and the air is directed downward and horizontally into the cold space with ductwork, as shown in Figure 35.

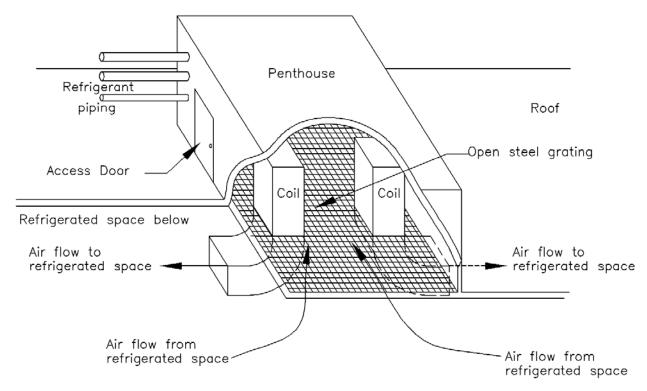


Figure 35: Evaporators Located in Penthouse.

Source: (Becker and Fricke 2005)

During a field investigation of refrigerated storage facilities in the US, Zhang and Groll (2005) found that penthouse installations for evaporators were a strongly growing trend, in which 50 percent to 75 percent of the installations in new plants incorporated penthouses.

Penthouse installations provide the following advantages:

- Service and maintenance are easier because piping, valves and controls are outside the refrigerated space
- Minimized maintenance and service costs
- Increased room within the refrigerated space
- The ceiling space is free for overhead equipment.
- Since piping, valves and controls are outside the refrigerated space, they are in no danger of being damaged from careless forklift operation.

A disadvantage of penthouse installation is that the piping and controls are out of sight, and thus, a concerted effort is required to provide proper service and maintenance. It should be noted that evaporators used in penthouse applications require heavier duty air movement components in order to meet the additional fan static pressure requirements

6.1.8 Defrosting of Refrigerant-to-Air Coil Evaporators

The evaporator, being the coldest surface in the cold room, attracts moisture from the air. This moisture condenses on the evaporator's surface and when the surface temperature is below freezing (32°F or 0°C), frost is formed. If this frost is not removed, the performance of the

evaporator will be degraded since frost formation increases the evaporator's resistance to heat transfer and restricts airflow. Under extreme conditions, the evaporator may even be rendered useless. Basic methods for defrosting an evaporator include air defrost, electric defrost, water defrost, and hot gas defrost (Stoecker 1998; Crawford, Mavec, and Cole 1992).

Prior to defrosting the coil, the refrigerant flow to the coil should be shut off for a short time to allow the refrigerant to exit the coil. Then, the fans are usually turned off and some form of heat is added to the coil. The melted ice drains into a drain pan and then away from the evaporator and out of the refrigerated space..

Air Defrost

In cold stores operating above 36°F (2°C), defrosting can be accomplished by simply turning off the refrigerant flow to the evaporator and allowing the fans to continue to operate, blowing room air over the evaporator, thus, melting the frost. The main disadvantage with this process is that it is very time consuming, however, it is low cost.

Electric Defrost

Electric defrosting is adaptable to any refrigerated space, regardless of temperature. However, it is not commonly used in industrial refrigeration. Two basic configurations of electric defrost can be used. In one configuration, electrically heated elements are placed within the coil during coil assembly. This is done by placing "dummy" tubes which contain electric heating elements into the coil bank. In the other configuration, electric heating elements are strapped to the outside of the fin/tube assembly. The advantage of this method is that the evaporator manufacturer does not have to provide additional tubing to compensate for the inactive "dummy" tubes. In either configuration, the size of the heating elements range from 10 kW to 40 kW per coil. Electric defrost has low initial cost but operating costs are high.

Water Defrost

Water defrosting can provide rapid defrost of coils at virtually all room temperatures. Water is sprayed over the coil and the mixture of water and melted frost flows into the drain pan. Water temperature should be between 60°F to 65°F (16°C to 18°C) and the flow rate should be between 2 to 4 GPM per square foot of coil face (1 to 3 liters per second per square meter of coil face). In a water defrost system, the water may be heated using waste heat recovered from the refrigeration system. In some cases, a remote evaporative condenser sump serves as a defrost water tank, with the water being heated during condenser operation. Other times, steam or electric resistance heaters are used to heat the water.

Hot Gas Defrost

During the hot gas defrost process, the evaporator coil is temporarily transformed into a condenser. The refrigerant becomes the heating medium, in the form of a vapor, which is supplied from the high pressure receiver or the compressor discharge. In this process, the vapor refrigerant condenses and releases its latent heat to defrost the coil. At the beginning of the defrost cycle, refrigerant condensation within the tubes is rapid and very little vapor

refrigerant makes its way to the end of the coil to be relieved through a pressure regulating valve. Any liquid or vapor refrigerant leaving the coil is eventually returned to the compressor via the coil suction line. The pressure regulating valve opens and closes during defrost to maintain a set pressure upstream of the valve, usually equivalent to approximately 60°F (16°C), which is high enough to melt the frost on the coils. In the later stages of the defrost cycle, vapor may pass through the pressure regulating valve. This will increase the compressor capacity requirements during defrost.

The typical sequence of an automated hot gas control system is as follows:

- The liquid refrigerant feed solenoid valve to the evaporator is closed.
- The fans continue to run to allow refrigerant to exit the coil.
- Once the liquid refrigerant has boiled out of the coil, the fans stop.
- The suction line valve is closed and a hot gas bypass line is opened, slowly pressurizing the coil. The defrost pressure regulator valve begins to function.
- The main hot gas solenoid valve is opened. Allow the defrosting process to continue until the frost has melted and is removed from the drain pan.
- The hot gas supply line solenoid closes, terminating the coil defrost.
- The suction bypass solenoid valve opens, slowly releasing the pressure in the coil. The pressure regulating valve ceases to function.
- The suction line stop valve opens and the liquid line solenoid valve opens, allowing liquid refrigerant to enter the evaporator.
- The fans are energized after the coil surface is below freezing, thus preventing moisture carry-over back to the refrigerated space. The coil is now refrigerating.

The specific timings between these events are automatically controlled and regulated by defrost controllers and computerized control systems.

An alternate approach to the pressure relief regulator is to use a liquid drainer. This is a device which operates similar to a steam trap, and allows only liquid refrigerant to pass from the coil. With a drainer, the pressure in the coil will continue to rise until nearly reaching the pressure of the hot gas supply. A suction gas by-pass bleeder valve arrangement is required to gradually relieve pressure at termination of defrost (Stoecker 1998).

Generally, 20 to 40 Btu per square foot of coil surface (230 to 450 kJ m⁻²) of hot gas is used for defrost. The volume of hot gas greatly varies throughout the defrost cycle. In the first 4 to 5 minutes, 60 percent to 70 percent of the total heat input will be consumed. Over the next 5 to 15 minutes, the remaining 30 percent to 40 percent will be used, with the end of the cycle using very little hot gas heat. Therefore, it is important to have an adequately sized pressure relief regulator or float drainer to accommodate the initial volumes. If a float drainer is not large enough to allow the liquid to drain from the coil, the bottom of the coil can become filled with refrigerant, thus impeding defrost.

The advantages of hot gas defrost are that the source of the defrosting medium is relatively inexpensive, the defrosting time is rapid, and the defrosting process can be completely automated. However, there must be an adequate source of hot gas, and hot gas defrosting can be potentially dangerous if not properly controlled. During both the initiation and termination of the hot gas defrost process, there is the potential for high pressure, high velocity vapor to be brought into contact with cold liquid, causing pressure shock waves which could rupture refrigerant lines and damage equipment. It is essential that hot gas defrost systems be correctly piped, sequenced and regulated.

On large central compressor plant systems, only one third of the evaporator capacity in service should be defrosted at a time. For example, if the refrigeration evaporator capacity in service is 150 tons, then only 50 tons of evaporator capacity should be defrosted at one time. During periods when there is insufficient load on the system, false loads may have to be created to operate the compressors during defrost cycles.

Evaporator Drain Pans

All air coils are equipped with drain pans that collect and remove the water vapor that has condensed from the air (Becker and Fricke 2005). If the coil is operating below 32°F (0°C), the coil must be defrosted periodically and a drain pan is necessary to collect and remove the molten frost. This drain pan must be kept warm so that the meltage does not refreeze in the drain pan. In hot gas defrost systems for spaces below 32°F (0°C), a pipe coil system containing hot defrost gas may be used to heat the insulated pan. In the case of a cooling coil which operates above the freezing temperature, it is not necessary to provide drain pan warming. It is also necessary to insulate drain pans to prevent condensation and drip from under the pan. In addition, the minimum slope to the drain should be ½ inch per foot (20 mm per meter) and the pan should be hinged or removable for sanitation and cleaning

Defrost Control

The required defrost frequency of a coil depends upon the air flow through the coil, the coil temperature and the moisture content of the air which, in turn, depends upon the outdoor ambient conditions and the type of product load. In refrigerated spaces, used for the long term storage of covered or sealed products where the doors are seldom opened, the required frequency of defrost can be quite low (Wilcox et al. 2007).

Defrost introduces significant heat into the refrigerated space. The facility must suspend its refrigeration to start the defrost cycle and heat is required to warm the metal tubes and fins of the coils. After defrost, the normal heat load that occurred during the defrost cycle must be overcome as well as the heat added to effect the defrost. These heat loads that are incurred during defrost can be substantial, so defrost strategies are used to minimize defrost cycles while keeping coils frost free and efficient.

Defrost may be initiated manually by an operator and scheduled for the same time(s) every day. In a food processing plant, defrost may be initiated manually during plant clean up. Another approach is to initiate and control defrosts with a dedicated local defrost controller, which is

essentially a time clock with multiple set points for each phase of the defrost cycle. A more sophisticated approach is to use a central computer control system to initiate and control defrosts, however most of these systems still initiate and control defrosts on a time schedule.

Advanced strategies for initiating defrost may make use of cumulative refrigerant flow rate as a measure of cumulative refrigeration load experienced by the coil. Other parameters that might be measured to initiate defrost include air pressure drop and/or air temperature drop across the coil, fan motor current draw, and frost thickness. Optical sensors can also be used to determine if the fins are blocked by frost.

Most industrial refrigeration defrost cycles last from 10 minutes to one hour and are terminated according to a time schedule. The required defrost period depends upon the amount of frost accumulation and the method of defrost. For hot gas defrost, the defrost period also depends upon the condensing temperature, the evaporator pressure regulating valve and the hot gas line size and insulation. The temperature of the hot gas leaving the evaporator could be measured as means of determining when defrost is complete with a rising gas temperature indicating that all of the frost has melted.

6.2 Compressors

It is not uncommon to find refrigerated storage facilities that use both piston and screw compressors. However, since the efficiency of current screw compressors is the same or higher than that of piston compressors, new refrigerated storage facilities typically incorporate screw compressors in their refrigeration systems (Zhang and Groll 2005).

6.3 System Type

6.3.1 Single-Stage or Two-Stage Compression

In a single-stage refrigeration system, there is one compression step between the evaporating pressure and the condensing pressure. Only one compressor is required for a basic single-stage refrigeration system. There are two operating pressures in the single-stage refrigeration system: a low pressure corresponding to the evaporating temperature and a high pressure corresponding to the condensing temperature.

In a two-stage refrigeration system, there are two compression steps between the evaporating pressure and the condensing pressure. The refrigerant flows through two compressors in series to perform the two compression steps in a basic two-stage refrigeration system. The two stages of compression result in three operating pressures in the two-stage refrigeration system: a low pressure corresponding to the evaporating temperature, an intermediate pressure that occurs between the two compressors, and a high pressure corresponding to the condensing temperature. A two-stage refrigeration system may be used where low evaporating pressure is required or where an intermediate evaporating pressure is required.

The advantages of a single-stage compression system include simplicity and low initial equipment cost. However, a single-stage system is limited by the suction pressure. When using screw compressors, the suction temperature limit for a single-stage systems is approximately -40°C (-40°F) (Zhang and Groll 2005). At the expense of higher initial equipment cost, a two-

stage compression system can be used to achieve lower suction pressure. Two-stage systems using screw compressors can provide evaporating temperatures of approximately -60° C (-76° F) (Zhang and Groll 2005).

For a given refrigerant and evaporating temperature, the choice of either single-stage or two-stage compression is dependent upon the condensing temperature. The condensing temperature varies throughout the year, being highest during the high-temperature summer season and lowest during the low-temperature winter season. If a refrigerated storage facility is to be located in a region where the temperature during the summer season is low, then a single-stage compression system may be considered. However, if a refrigerated storage facility operates for a significant period of time in conditions where the outside ambient temperature is high, then a two-stage compression system should be considered (Zhang and Groll 2005).

Two-stage compression systems offer additional benefits, including subcooling of liquid refrigerant (also called flash gas removal) and desuperheating of discharge gas. These two processes are performed in the intercooler, a vessel located between the low-stage and high-stage compressors. The intercooler cools the discharge gas of the low-stage compressor and also cools the refrigerant in the low-stage portion of the system (Zhang and Groll 2005). The intercooler may either be a flash-type intercooler or a shell-and-coil type intercooler. It has been shown that refrigeration system efficiency is about 2 percent higher when using a flash-type intercooler as compared to a shell-and-coil type intercooler (Zhang and Groll 2005).

A single-stage compressor consumes approximately 18-19 kW per 2.8 cubic meters (100 cubic feet) per minute when operating at full load. A two-stage system, on the other hand, consumes approximately 16-17 kW per 2.8 cubic meters (100 cubic feet) per minute. Thus, a two-stage system can provide an energy savings of around 11-13 percent compared to a single-stage system (Lekov et al. 2009).

6.4 Motors

6.4.1 Variable Frequency Drive Basics

All 3-phase induction motors are designed to operate at one speed; typically 1200, 1800 or 3600 rpm. Since electric utilities provide power at 60 Hz, motor speed is determined by winding configurations within the motor. As a result, equipment driven by induction motors (including fans and compressors) are constrained to a single speed.

By using variable frequency drives (VFD), the speed of nearly any induction motor can be controlled from 0 percent to 100 percent. This is done by first converting the 60 Hz sine wave from the utility company to DC power. Using a process called pulse-width modulation, the VFD then sends pulses of varying width and polarity to the motor. The resulting voltage waveform is no longer sinusoidal, however, the resulting current draw of the motor is approximately sinusoidal (Wilcox and Morton 1998).

Evaporator & Condenser Fan Control Strategies

Under the most basic configuration, evaporator fans are operated non-stop, with the back-pressure regulator (BPR) controlling refrigerant pressure and temperature for room

temperature control. Energy can be reduced by cycling evaporator fans on and off to reduce fan energy. Fan energy use becomes proportional to run time. This can be achieved through a computer control system, or manually. Some owners simply remove fuses or throw disconnects during periods of light load to achieve savings(Wilcox 2001).

Another alternative is Variable Frequency Drive (VFD) control. In general, a VFD takes the 480-Volt, 60-cycle utility power and turns it into 680-Volt DC power. The VFD then sends voltage pulses of varying width and polarity to the motor. The motor speed can be adjusted to any frequency between 0 and 60 Hz (with proper consideration for mechanical or thermal limitations of the motor and driven equipment). A typical VFD is shown in Figure 36.



Figure 36: Typical Variable Frequency Drive (VFD).

Source: (Wilcox 2001)

The "affinity laws" predict a cubic relationship between fan speed and shaft horsepower. This means that at 50 percent fan speed, we achieve 50 percent air movement with only 50 percent, or 12.5 percent power. Realistically the value is an exponent of 2.5 to 2.7, reducing electrical input power to the range of 15 percent to 18 percent at half speed. Any reduction in evaporator fan power reduces the heat load that must be removed by the compressors and condensers, thereby providing additional savings.

Condenser fans are usually cycled to control condenser capacity and system condensing pressure. This cycling is achieved through a computer control system, or simple Penn or Mercoid switches. Similar to evaporator fans, condenser fans follow the affinity laws, resulting in dramatic savings at reduced speed.

Evaporator Fan VFD Control

Many control strategies for evaporator fans are rather crude, consisting of either continuous operation or simple on/off control. Since fan power follows a cubic relationship with flow rate, it would be more energy efficient to use variable speed fans on each evaporator. Less energy is required to run fans continuously at a slow speed than it is to cycle the fans on and off.

Evaporator fan VFD control is typically the single greatest opportunity to reduce refrigeration energy use(Wilcox 2001). In refrigerated facilities, fans are typically operated continuously at full speed. However, following room pull down, fan speed could be reduced as much as 50 percent. There is little incentive to reduce speed below 50 percent speed, since power has already been reduced by over 80 percent, and additional speed reduction only diminishes airflow in the room. In general, one VFD is installed for each storage room. Where VFDs are installed on common storages, one VFD is installed per refrigeration zone. It is important that the VFD be correctly sized and applied. Issues of harmonics and motor protection require specification of appropriate input reactors, output dV/dt filters, and inverter-rated motors for a successful and reliable application.

One benefit of evaporator fan VFD control is smooth temperature control. Although conventional fan cycling saves energy, there is an inherent room air temperature swing when using fan cycling.

Condenser Fan VFD Control

Rather than cycling condenser fans for capacity control, VFD control can be utilized (Wilcox 2001). Similar to evaporator fans, the affinity laws provide excellent savings relative to simple cycling. However, a second convincing benefit also plays a part in the decision to utilized speed control. VFD control eliminates the rapid cycling of the condenser fan required for proper pressure control. With the VFD, average condensing pressure is smoother and lower. Since lower condensing pressure reduces compressor energy use, condenser fan VFDs often achieve compressor energy savings that is larger than the fan energy savings. Condenser belt and sheave wear is also reduced as a result of VFD control

Compressor Part Load Operation and Screw Compressor VFD Control

Compressor part load performance plays a significant role in energy efficiency as well (Wilcox 2001). Although reciprocating compressors unload relatively efficiently, screw compressors are another matter. As a screw compressor unloads, it becomes less efficient. The brake horsepower (BHP) per ton of refrigeration (TR) degrades. Energy efficiency solutions for this potential problem vary in complexity and completeness. Often, operating a screw compressor unloaded can be avoided by a diverse selection of machines that can be properly sequenced by the control system. In other systems, reciprocating compressors are used to efficiently trim

system capacity and power. However, in some systems, there is no avoiding operation of a screw compressor in the unloaded condition.

In this situation, a VFD can be installed for the screw compressor. Rather than using the conventional slide valve for unloading, the compressor speed is reduced from 3600 to 1800 rpm, keeping the slide valve fully open. Once at 1800 rpm, the slide valve is then closed to further reduce capacity. The effectiveness of compressor VFD control is dependent on a variety of issues, including the shape of the basic compressor part load power curve. However, there are certainly times when this VFD application is viable.

Care should be taken to reduce resonant vibration when using variable speed drives in conjunction with compressors. Elimination of certain frequencies with variable speed drive operation may be necessary in order to avoid operation which causes severe vibration (Pacific Gas and Electric Company 2006).

6.5 Refrigerants

6.5.1 Refrigerant Selection

The following list provides the properties that an ideal refrigerant should possess (ASHRAE 2009; Kuehn, Ramsey, and Threlkeld 1998):

- Positive evaporating gauge pressures: Prevents possible leakage of atmospheric air into the system during operation.
- Moderately low condensing pressures: Permits the use of lightweight equipment and piping on the high-pressure side of the refrigeration system.
- High critical temperature: Prevents unduly large power requirements.
- High latent heat of vaporization: Provides a high refrigerating effect per unit mass of refrigerant circulated.
- High heat-transfer characteristics: Reduces the surface area required in heat exchangers.
- Low viscosity: Ensures minimal pressure drop through the piping, heat exchangers, and other components.
- Inertness and stability: The refrigerant should be inert to reactions with materials of the system. It should be stable.
- Non-toxicity: The refrigerant should not be poisonous to humans and to foodstuffs.
 Toxicity ratings of refrigerants may be found in the 2001 ASHRAE Handbook of Fundamentals.
- Non-flammability: The refrigerant should not burn or support combustion in any concentration with atmospheric air. Flammability ratings of refrigerants may be found in the 2001 ASHRAE Handbook of Fundamentals.
- Low ozone-depletion potential: The refrigerant should not cause depletion of the ozone layer in the atmosphere.
- Low greenhouse potential: The refrigerant should not contribute to the greenhouse effect, or global warming effect.

- Low cost of refrigerant.
- Easy leakage detection.
- Satisfactory oil solubility.
- Low water solubility.

Presently, there is no single refrigerant available which can satisfy all of the above requirements. The most widely used refrigerant for large industrial applications such as refrigerated warehouses is ammonia (R-717). Smaller refrigerated storage facilities may utilize HFC refrigerants such as R-404A, R-407A or R-407C.

6.5.3 Halocarbon Refrigerants

The earliest refrigeration systems (circa the late 1800s) utilized naturally occurring and readily available working fluids such as ammonia, carbon dioxide, and sulfur dioxide. However, these substances are toxic, and during the early 20th century, with advances in chemistry, they were rapidly replaced with synthetic refrigerants.

These synthetic refrigerants, known as halocarbons, are made up of some or all of the following elements: carbon, hydrogen, chlorine and fluorine. Several varieties of halocarbons have been developed including chlorofluorocarbons (CFCs), hydrogenated chlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs).

When released to the atmosphere, CFCs remain there for many years and diffuse into the stratosphere. Once these molecules decompose, the release of chlorine destroys the ozone layer (Stoecker 1998; ASHRAE 2009; Kuehn, Ramsey, and Threlkeld 1998; IIR 1990). Furthermore, in the lower atmosphere, CFCs absorb infrared rays and cause global warming.

Hydrogenated halocarbon (HCFC) refrigerants, of which R-22 is an example, contain a hydrogen atom. These molecules are not as stable as CFCs, so when HCFCs are released into the atmosphere, they decompose before reaching the ozone layer. Thus, HCFCs are less damaging to the ozone layer.

HFC refrigerants, another group of halocarbons, break down before reaching the stratosphere. Thus, the ozone depleting potential of these refrigerants is nearly zero.

Table 9 gives the ozone depleting potential (ODP) and global warming potential (GWP) of several refrigerants as compared to R-11.

Table 9: Ozone Depleting Potential (ODP) and Global Warming Potential (GWP) of Several Refrigerants as Compared to R-11.

Source: (Becker and Fricke 2005)

Refrigerant	Chemical Formula	ODP	GWP
CFC-11	CFCI ₃	1.00	1.00
CFC-12	CF ₂ Cl ₂	1.00	3.20

Refrigerant	Chemical Formula	ODP	GWP
CFC-115	CCIF ₂ CF ₃	0.6	10.6
HCFC-22	CHCIF ₂	0.055	0.3
HFC-32	CH_2F_2	0	0.12
HCFC-123	CHCl ₂ CF ₃	0.02	0.02
HFC-125	CHF ₂ CF ₃	0	0.63
HFC-134a	CH ₂ FCF ₃	0	0.31
HFC-143a	CH ₃ CF ₃	0	0.76

The adoption of the Montreal protocol has limited the use of certain halogenated refrigerants, such as R-12, which is used in refrigeration plants, and R-11, which is used as a blowing agent for insulation. According to this protocol, complete cessation of the use of HCFCs should occur by 1 January 2030. Thus, substitute refrigerants must be found. Currently, HFC refrigerants are used as substitutes for CFC and HCFC refrigerants. For example, R-134a is being used as a substitute for R-12, R-123 or R-141B are used as substitutes for R-11, and R-507 is used as a substitute for R-502. Suitable substitutes for R-22 include R-404A, R407A, R-407C and R-410A.

Due to the high global warming potential of the HFC refrigerants currently in use, there has been a renewed interest in using natural refrigerants such as carbon dioxide and ammonia (although ammonia has been, and still is, widely used as a refrigerant in industrial refrigeration applications).

6.5.4 Natural Refrigerants

Natural refrigerants have little impact on the atmosphere's ozone layer or global warming. For example, carbon dioxide has no ozone depletion potential (ODP = 0) and negligible direct global warming potential (GWP = 1) when used as a refrigerant in closed cycles, while ammonia has both no ozone depletion potential (ODP = 0) and no global warming potential (GWP = 0).

Ammonia (R-717) is an excellent refrigerant which has been used for the past 130 years, mostly in large industrial systems such as cold stores. Due to its non-flammability, non-toxicity, and low global impact, carbon dioxide (R 744) has proven to be a viable alternative in several applications. In large low temperature (-30°C to -50°C) industrial systems, ammonia/carbon dioxide cascade systems have been developed where the ammonia (high cascade) is confined to the machine room while the carbon dioxide (low cascade) is circulated to spaces where the cooling is required, such as storage spaces and production areas where food is being processed and frozen. In this way, ammonia is not circulated to these areas, so that in case of an ammonia leak, neither the staff nor the food being processed and frozen would be affected.

Ammonia (R-717)

Ammonia is one of the oldest refrigerants and is widely used in larger industrial applications (Stoecker 1998; ASHRAE 2009; Kuehn, Ramsey, and Threlkeld 1998; IIR 1990; IIAR 1993). It has excellent thermodynamic properties, and in fact, in a standard vapor-compression refrigeration cycle, ammonia refrigerant produces the largest COP as compared to all other currently available refrigerants (Zhang and Groll 2005). Its boiling point of –28°F (–33°C) at 1 atm pressure allows positive evaporating pressures in a majority of refrigeration applications. Its critical temperature of 271°F (133°C) at 1657 psia (11.4 MPa) is relatively high, while its freezing temperature of –108°F (–78°C) is sufficiently low. One of the outstanding characteristics of ammonia is its high latent heat of vaporization. Ammonia is also cheap and it has high heat transfer characteristics. It does not have any ozone depleting potential (ODP) or global warming potential (GWP) and most lubricants are immiscible in ammonia. In addition, ammonia is globally available since it is primarily used as a fertilizer material.

In the presence of water, ammonia strongly attacks copper and cuprous alloys. Thus, ammonia is never used with cuprous metals.

The primary disadvantages of ammonia are that it is toxic and flammable within a narrow range of conditions. Also, in the case of a leak in a storage space, ammonia has been found to affect the quality of stored food products(Duiven and Binard 2002). Fortunately, ammonia can be easily detected by smell in extremely low concentrations, typically 53 parts per million. Exposures of one to two hours at this low level concentration of ammonia presents no serious injury. However, at concentrations of 300 to 500 parts per million, ammonia becomes dangerous within 30 to 60 minutes of exposure. Serious injury will occur within minutes of exposure at concentrations of 5,000 to 10,000 parts per million. Nonetheless, if it is used in a properly designed refrigeration plant that is well maintained, ammonia is acceptable in terms of safety.

Carbon Dioxide (R-744)

While ammonia is well suited as a refrigerant for low temperature applications such as industrial food freezing and storage, it has the disadvantages of acute toxicity and relatively large gas densities at low temperature (Pearson 2001). The problems associated with toxicity are minimized by installing alarm systems and developing emergency procedures to be used in the event of a leak or spill.

Ammonia refrigeration plants can be designed for operation down to -60° C (-76° F), however, extremely large compressors are required due to ammonia's relatively large gas volume at low temperature. Thus, ammonia systems are typically designed for temperature no lower than -35° C (-31° F) (Pearson 2001).

Carbon dioxide is a natural refrigerant that is relatively non-toxic and has a relatively high gas density at low temperature. The triple point of carbon dioxide is –56.6°C (–69.9°F) and 418 kPa (gauge) (61.5 psig). Thus, for reliable operation, a pumped liquid refrigeration system using carbon dioxide should operate above –55°C (–67°F) to prevent the refrigerant from solidifying (Pearson 2001).

Figure 37 shows the density of ammonia and carbon dioxide gas versus temperature. For a typical condition of -40°C (-40°F), it can be seen that the density of carbon dioxide is about 40 times that of ammonia. While the latent heat of carbon dioxide is about one fifth that of ammonia (300 kJ/kg compared to 1,400 kJ/kg), the swept volume required by carbon dioxide is about one eighth that of ammonia. Thus, one CO₂ compressor gives the same refrigerating effect as eight similar ammonia compressors (Pearson 2001).

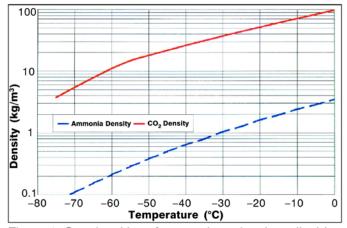


Figure 1: Gas densities of ammonia and carbon dioxide. Figure 37: Gas Densities of Ammonia and Carbon Dioxide.

Source: (Pearson 2001)

Although carbon dioxide is mentioned in connection with global warming, it is with respect to the emissions from burning fossil fuels. The amount of carbon dioxide contained in a large industrial refrigeration plant is insignificant when compared to the amount produced by burning fossil fuels. Thus, the environmental impact of venting small amounts of carbon dioxide from a refrigeration system is negligible (Pearson 2001).

It has been estimated that refrigeration and air conditioning account for approximately 15 percent of all energy consumed worldwide (Pillis 2009). Thus, improving the energy efficiency of refrigeration and air conditioning systems would have a positive impact on both the energy resources and emissions of greenhouses gasses.

While CO₂ has recently gained considerable attention as a natural refrigerant with low toxicity, no flammability and low global warming potential, it suffers from low cycle efficiency (Pillis 2009).

Carbon dioxide has a relatively low critical temperature which means that it will not condense at temperatures above 31°C (87.8°F). Since condensing temperatures can often exceed this level, the applicability of CO₂ is limited to cascade systems, in which the CO₂ is condensed in a heat exchanger at a relatively low temperature. The energy from the CO₂ is then transferred to another refrigerant which condenses at a higher temperature, releasing energy to the environment. Transcritical CO₂ systems, or non-condensing systems, can be used, but their cycle efficiency is considerably lower than conventional sub-critical systems. Transcritical systems are used in niche markets where something other than energy savings is of interest, such as small component size, high heat rejection temperature, etc. (Pillis 2009).

Pillis (2009) presents the results of thermodynamic analyses performed on a CO₂/ammonia cascade refrigeration system and a two-stage ammonia refrigeration system. Assuming ideal (isentropic) compression and a cascade approach temperature of 9°F, it was found that the CO₂/ammonia cascade system required approximately 15 percent more energy than a two-stage ammonia system operating between the same evaporator and condenser temperatures. In addition, using actual screw compressor operating efficiencies, it was estimated that CO₂/ammonia cascade systems consume approximately 6 percent more energy at -40°C (-40°F) evaporating temperature than two-stage ammonia systems. Furthermore, CO₂/ammonia cascade systems with reciprocating compressors in the CO₂ stage and screw compressors in the ammonia stage were estimated to consume 8 percent more energy than two-stage ammonia systems with screw compressors on both the low and high stages.

However, it was noted that CO₂/ammonia cascade systems do have several advantages over two-stage ammonia systems. Due to carbon dioxide's greater gas density as compared to ammonia, smaller low stage compressors and smaller low stage pipe sizes can be used in the CO₂/ammonia cascade system. In addition, the ammonia charge can be significantly reduced in CO₂/ammonia systems since the CO₂ is circulated to the storage room evaporators while the ammonia is confined to the mechanical room (Pillis 2009).

6.5.5 Total Equivalent Warming Impact (TEWI)

Chlorofluorocarbon refrigerants, such as R-11 and R-12, are molecules composed of chlorine, fluorine and carbon. These molecules are chemically stable, thus allowing them to rise into the stratosphere when released. Such a release might occur when there is a leak in a refrigeration system or when a CFC is used as a blowing agent to create insulation. At the high altitudes in the stratosphere, ultraviolet radiation from the sun causes the chlorine atoms in the CFC molecules to break free. This chlorine then reacts with the ozone (O₃) in the stratosphere, creating diatomic oxygen (O₂) and chlorine. The reduction in the ozone due to the reaction with chlorine allows more ultraviolet radiation to reach the earth's surface, thereby increasing the risk of cancer to humans.

To prevent the depletion of the ozone layer, the Montreal Protocol was established in 1987 to eliminate the production and use of CFCs as well as hydrogenated halocarbons (HCFCs).

The environmental impact of refrigerants is described by the Ozone Depletion Potential (ODP) and the Global Warming Potential (GWP). The ozone depletion potential describes a refrigerant's ability to destroy the ozone layer in the Earth's atmosphere relative to that of R-11. The ozone depletion potential of R-11 is defined to be 1. The global warming potential describes a refrigerant's ability to warm the Earth's atmosphere relative to that of carbon dioxide for a period of 100 years. The global warming potential of carbon dioxide is 1 integrated over a time period of 100 years.

Another measure of environmental impact is the Total Equivalent Warming Impact (TEWI). TEWI is an index which includes the effects of CO₂ production due to the energy use of the refrigeration system and the effects of the release of refrigerant over the useful life of the refrigeration system. The warming impact associated with CO₂ emissions due to energy use are

referred to as indirect effects while the warming impact due to the release of refrigerant is referred to as direct effects (Lommers 2002). The total effect on the environment must be given for a period of time, which is typically 100 years (Baxter, Fischer, and Sand 1998).

Figure 38 shows the normalized radiative forcing, or the potential for temperature change, from the release of greenhouse gases for a refrigeration system. The lower portion of the curve (shown in red) illustrates how the amount of CO₂ from energy use changes over time in the atmosphere. Initially, there is a peak in CO₂ output during the early stages of the refrigeration system. Over time, a portion of the CO₂ is gradually removed through the natural processes of plants, oceans and weather. The upper portion of the curve (shown in green) illustrates the global warming effect of refrigerant emissions from the refrigeration system and its gradual decrease over time. The total environmental impact is obtained from the area under both curves, including the impact of energy use and refrigerant emissions (Baxter, Fischer, and Sand 1998).

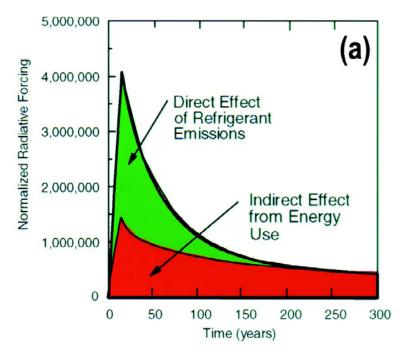


Figure 38: Radiative Forcing from a Refrigeration System.

Source: (Baxter, Fischer, and Sand 1998)

The TEWI for a refrigeration system can be estimated from the total amount of refrigerant released during the lifetime of operation of the system and the total energy used by the refrigeration system over its useful lifetime as follows:

$$TEWI = \left(m_{refrig}\right) \left(GWP_{refrig}\right) + \left(\alpha\right) \left(E_{annual}\right) \left(L_{years}\right)$$
(10)

where m_{refrig} is the mass of refrigerant released over the useful life of the system, GWP_{refrig} is the global warming potential of the refrigerant, α is a conversion of energy use into CO₂ emissions, E_{annual} is the annual energy usage of the system and L_{years} is the useful life of the system (Baxter, Fischer, and Sand 1998).

Since many industrial refrigeration systems utilize ammonia as the refrigerant, and ammonia has a GWP of 0, the direct impact on global warming due to ammonia leakage is minimal. However, the energy consumption of an ammonia-based industrial refrigeration system has a significant indirect impact on global warming. This is due to the fact that most refrigeration systems receive their electrical energy from fossil-fuelled generating stations. It has been estimated that CO₂ production could be as high as 0.8 kg per kWh of electrical energy (Lommers 2002). Therefore, improvements in the energy efficiency of a refrigeration system can significantly lessen the system's impact on global warming.

6.5.6 Life Cycle Climate Performance (LCCP)

The selection of an appropriate refrigeration system and/or refrigerant should be based on several factors, including the global warming potential (GWP) of the refrigerant, the energy consumption of the refrigeration system over its operating lifetime, and the leakage of refrigerant over the system lifetime. For example, focusing on energy efficiency alone may overlook the significant environmental impact of refrigerant leakage.

Life Cycle Climate Performance (LCCP) is a method to determine the environmental impact of refrigeration system design, refrigerant selection and system operation over its operating lifetime. The environmental impact of the refrigeration system is measured by estimating the system's greenhouse gas emissions in terms of carbon dioxide equivalent emissions. The carbon dioxide equivalent emission is the quantity of carbon dioxide that would have the same GWP as the greenhouse gas emissions of the refrigeration system under consideration (Hafner, Nekså, and Pettersen 2004; Horie et al. 2010; Johnson 2004; Papasavva, Hill, and Andersen 2010; Spatz and Motta 2004; Zhang et al. 2011). LCCP is intended to provide a more comprehensive environmental impact analysis than TEWI.

LCCP includes the effects of direct and indirect emissions to determine the environmental impact of the refrigeration system:

$$LCCP = \sum (Direct\ emissions + Indirect\ emissions)$$
 (11)

where *LCCP* is a measure of the carbon dioxide equivalent emissions (kg CO_{2e}) of the refrigeration system. Direct emissions include those related to the direct release of refrigerant from the system, including annual leakage, loss at the end-of-life of the system and loss during service events. Indirect emissions include those associated with the energy to manufacture, decommission, and recycle the refrigeration system, as well as the emissions associated with the production and distribution of the electrical energy required to operate the refrigeration system. Thus, LCCP analysis attempts to provide details of the "cradle-to-grave" environmental impact of the refrigeration system.

Direct Emissions

The direct emission from the refrigeration system, E_{direct} , in terms of the carbon dioxide equivalent (kg CO_{2e}), is calculated as follows:

$$E_{direct} = E_{leakage} + E_{service} + E_{accidents} + E_{EOL} + E_{prod/trans}$$
 (12)

where $E_{leakage}$ is the carbon dioxide equivalent emission of the total leakage of refrigerant from the system over its operating lifetime, $E_{service}$ is the CO₂ equivalent emission of the total refrigerant release occurring during all refrigeration system service events over the system operating lifetime, $E_{accidents}$ is the CO₂ equivalent emission associated with accidental refrigerant loss, E_{EOL} is the CO₂ equivalent emission associated with the release of refrigerant at the end of the system life (due to refrigerant recovery inefficiencies), and $E_{prod/trans}$ is the CO₂ equivalent emission due to leaks which occur during production and transport of the refrigerant.

The carbon dioxide equivalent of the leakage of refrigerant from the system over its operating lifetime, *Eleakage*, is calculated as follows:

$$E_{leakage} = (GWP_{100})(x_{leak})(m_{refrig})(t)$$
(13)

where GWP_{100} is the 100 year integration time horizon (ITH) global warming potential of the refrigerant, x_{leak} is the fraction of the total refrigerant charge which leaks from the system annually (1/yr), m_{refrig} is the refrigerant charge (kg) and t is the useful service life of the refrigeration system (yr). The GWP values for several refrigerants are given in Table 10.

Table 10: GWP Values and Manufacturing Emissions for Several Refrigerants.

Source: (ASHRAE 2009; Spatz and Minor 2008; A.D. Little 2002)

Refrigerant	GWP ₁₀₀	Manufacturing GWP
R32	675	11
R134a	1430	13
R404A	3900	18
R717	1	2
R744	1	1
R1234yf	4	9

The direct CO₂ equivalent emissions which occur during the regular servicing of the refrigeration system, *Eservice*, is calculated as follows:

$$E_{service} = (GWP_{100})(x_{service})(m_{refrig})(n)(t)$$
(14)

where $x_{service}$ is the fraction of the total refrigerant charge which is released during each system service event and n is the system service interval (number of service events per year).

The carbon dioxide equivalent of the refrigerant release which occurs at the end-of-life of the system, *Eeol.*, typically due to inefficiencies associated with refrigerant recovery, is determined as follows:

$$E_{EOL} = (GWP_{100})(x_{EOL})(m_{refrig})$$

$$\tag{15}$$

where x_{EOL} is the fraction of the total refrigerant charge which is released at the end-of-life of the system.

It is typically more difficult to quantify the remaining direct emissions terms ($E_{accidents}$ and $E_{prod/trans}$). However, since their contribution to direct emissions is very small, they may be neglected.

Indirect Emissions

The indirect emission from the refrigeration system, $E_{indirect}$, in terms of the carbon dioxide equivalent (kg CO_{2e}), is calculated as follows:

$$E_{indirect} = E_{e,op} + E_{man,sys} + E_{man,ref} + E_{e,trans} + E_{e,EOL,sys} + E_{e,EOL,ref}$$
(16)

where $E_{e,op}$ is the CO₂ equivalent emission associated with the production and distribution of the energy required to operate the refrigeration system over its lifetime, $E_{man,sys}$ and $E_{man,ref}$ are the CO₂ equivalent emissions associated with the energy consumed to manufacture the refrigeration system and the refrigerant, respectively, $E_{e,trans}$ is the CO₂ equivalent emission associated with the transport of the refrigeration system, and $E_{e,EOL,sys}$ and $E_{e,EOL,ref}$ are the CO₂ equivalent emissions associated with the energy consumed to recycle the refrigeration system and the refrigerant at the end-of-life, respectively.

The carbon dioxide equivalent associated with the production and distribution of the electrical energy required to operate the refrigeration system over its lifetime, $E_{e,op}$, is determined as follows:

$$E_{e,op} = (x_{energy})(E_{electric})(t)$$
(17)

where x_{energy} is the carbon dioxide equivalent emission factor associated with the production and distribution of electrical energy (kg CO_{2e}/kWh of delivered electricity), $E_{electric}$ is the annual electrical energy consumption of the refrigeration system (kWh/yr), and t is the useful operating lifetime of the refrigeration system (yr). The carbon dioxide emission factors for electrical energy production and distribution depend upon the corresponding grid interconnect region were the electricity is generated, and accounts for the various sources of the electricity in the region (i.e., coal-fired, nuclear, hydropower, solar, etc.). These emission factors may be obtained from (Deru and Torcellini 2007).

The term "embodied energy" may sometimes be used to refer to the energy consumed to manufacture the refrigeration system and the refrigerant. Since energy consumption usually causes greenhouse gas emissions, the sum of $E_{man,sys}$ and $E_{man,ref}$ is the CO₂ equivalent emissions associated with the embodied energy of the refrigeration system.

The carbon dioxide equivalent emission associated with the energy required to manufacture the refrigeration system, $E_{man,sys}$, is calculated as follows:

$$E_{man,sys} = \sum_{i} x_{i,man,sys} m_{i} \tag{18}$$

where $x_{i,man,sys}$ is the CO₂ equivalent emission factor associated with the manufacture of component i (kg CO_{2e}/kg) and m_i is the mass of component i (kg). Typically, each component of the refrigeration system (i.e., compressor, condenser, evaporator, refrigerant piping) can be assumed to be constructed of various fractions of aluminum, copper, steel and plastic. The carbon dioxide equivalent emission factors for these base materials can be obtained from (Papasavva, Hill, and Andersen 2010), and are shown in Table 11.

Table 11: Material Properties and Manufacturing Emissions

Source: (Papasavva, Hill, and Andersen 2010)

Material	Density (kg/m³)	Manufacturing Emissions (kg CO _{2e} /kg)
Aluminum	2701	1.6
Copper	8932	3.3
Steel	7853	1.6
Plastic	1000	3.0

Similarly, the carbon dioxide equivalent emission associated with the energy required to manufacture the refrigerant, $E_{man,ref}$, is calculated as follows:

$$E_{man,ref} = \sum_{i} x_{i,man,ref} m_i \tag{19}$$

where $x_{i,man,ref}$ is the CO₂ equivalent emission factor associated with the manufacture of refrigerant i (kg CO_{2e}/kg) and m_i is the mass of refrigerant i (kg). The CO₂ equivalent emission factors for the production of the refrigerants can be obtained from A.D. Little (2002), and are shown in Table 10. Note that the carbon dioxide equivalent emissions for the manufacture of the refrigerant should include that associated with the initial charge as well as that to replenish the leakage and service releases.

The carbon dioxide equivalent emissions associated with the energy to transport the refrigeration system and to recycle both the refrigerant and the refrigeration system at the end-of-life of the system may be difficult to quantify. However, since their contributions to indirect emissions are very small, particularly compared to the indirect emissions associated with energy consumption, these emissions may be neglected.

6.5.7 Safety, Toxicity and Flammability

ANSI/ASHRAE Standard 34, Number Designation and Safety Classification of Refrigerants, provides a classification of refrigerants according to safety (ASHRAE 2004). Two basic characteristics, flammability and toxicity, are used as the basis for the classification. The classification system consists of two levels of toxicity and three levels of flammability.

The ANSI/ASHRAE Standard 34 classification for toxicity is based on chronic exposure limits defined as follows (ASHRAE 2004):

- Class A: Toxicity has not been identified at concentrations less than or equal to 400 ppm by volume, based on data used to determine threshold limit value/time-weighted average (TLV/TWA) or consistent indices.
- Class B: There is evidence of toxicity at concentrations below 400 ppm by volume, based on data used to determine TLV/TWA or consistent indices.

The threshold limit value/time-weighted average (TLV/TWA) originates with the American Congress of Governmental Industrial Hygienists (ACGIH) and is defined as the threshold limit value/time-weighted average exposure that a worker can be experience during a normal 40 hour work week without any adverse health effects.

ANSI/ASHRAE Standard 34 classifies refrigerants into the three flammability categories, 1, 2, 3, as follows (ASHRAE 2004):

- Class 1: No flame propagation in air at 70°F and 14.7 psia.
- Class 2: Lower flammability limit (LFL) greater than 0.00625 lb/ft³ at 70°F and 14.7 psia and heat of combustion less than 8174 Btu/lb
- Class 3: Highly flammable as defined by LFL less than or equal to 0.00625 lb/ft³ at 70°F and 14.7 psia or heat of combustion greater than or equal to 8174 Btu/lb

6.6 Refrigeration System Monitoring and Control

Energy use and facility management are vital aspects of the green, sustainable, energy efficient, cost-effective operation of a refrigerated storage facility. After the facility has been built and put into service, it is the responsibility of the facility manager to monitor how and where energy is being used within the facility. With this knowledge, measures can be taken to manage the load and reduce the energy consumption and cost per unit of energy, thereby reducing operating costs and increasing sustainability.

The use of a computer-based energy management system is recommended. The importance of establishing and maintaining an energy accounting system to track energy consumption is also emphasized. Using information from the computer-based energy management system, utility invoices, printouts from time of use meters, recordings of temperature and relative humidity, sub-metered data, infrared scans, etc., a database of past energy usage may be created. This database may then be used to identify energy conservation opportunities (ECOs), leading to sustainable optimization of the facility and its refrigeration system. The energy accounting system in conjunction with regular maintenance will ensure that the equipment is operating at optimum condition, thereby minimizing waste and environmental impacts

6.6.1 Controls

Since the cooling loads experienced by the refrigeration system vary over time due to the continuously changing conditions within and around the storage facility, it is necessary to adjust the refrigeration system equipment during operation to maintain maximum efficiency. This can be achieved either automatically or manually. Automatic control, however, is more accurate and significant energy savings can be achieved. Studies in China show that automatic control of the refrigeration system could provide an energy savings up to 40 percent as compared to manual control (Zhang and Groll 2005). Another advantage of automatic control is that the amount of operational staff required is minimized, thus reducing operating costs (Zhang and Groll 2005).

6.6.2 Sub-metering

With the large utility bills associated with the operation of refrigerated storage facilities, it is imperative that sub-metering of the refrigeration system be employed to monitor system performance. The energy usage of each major component of the refrigeration system should be monitored, especially compressor motors and evaporator and condenser fans. Sub-metering allows for the identification of energy-saving opportunities (BFFF 2009).

6.6.3 Computer controls

A refrigeration control system can be considered a "backbone" energy efficiency upgrade (Wilcox 2001). Although the control system can save tremendous amounts of energy, it also provides a basis for proper control of VFDs. The control system can directly reduce energy use through evaporator fan cycling, compressor sequencing, automated suction pressure optimization, and better condensing pressure control relative to pressure switches. The control system also plays an important role in monitoring and managing room temperature and atmosphere conditions. Control system costs can vary widely, based on the size of the facility and whether or not atmosphere maintenance is required. A small system than only controls refrigeration may cost \$25,000 to \$40,000, while the cost for a large CA complex with atmosphere control could reach \$75,000 to \$100,000 or more.

6.6.4 Controls

Distributed control system (DCS)

The control of refrigeration systems may range in complexity from simple manual controls in which an operator physically changes the settings, to electro-mechanical controls in which electronic or pneumatic circuits adjust settings, to programmable logic controllers which use solid-state hardware and computer control to adjust settings. If high energy efficiency is to be achieved, then a SCADA system with PLCs and computer control is required (Lekov et al. 2009).

CHAPTER 7:

Operations: Energy Efficiency Measures

7.1 Refrigeration System Efficiency

Industrial refrigeration systems are used in the food processing, food preservation, chemical production and numerous other special industries. Each refrigeration system is unique and system design and operation tends to be more of an art form than a science (Manske, Reindl, and Klein 2001).

Energy required for refrigeration constitutes the major cost of operating a refrigerated storage facility. Thus, the use of energy efficient refrigeration technologies and strategies will reduce operating costs and increase the sustainability of the facility.

Even though a refrigeration system may be producing the desired result, it may not be operating at maximum efficiency. In an effort to reduce electrical usage and costs, it is necessary to critically evaluate system design and operating strategies.

7.2 Energy Efficiency Measures

Most refrigeration systems are designed according to a peak refrigeration load based on the hottest summer operating conditions. However, there are significant periods of the year during which ambient temperatures are much less than the peak summer conditions. During cold weather, an opportunity exists to operate the refrigeration system at a lower condensing pressure, thereby increasing system efficiency (Wilcox 2001).

However, the condensing pressure cannot be lowered too far. Screw compressors with liquid injection oil cooling may not work properly below 125 psig to 140 psig. Gas pressure systems may not operate correctly due to controlled-pressure receiver (CPR) pressure or other system limitations (Wilcox 2001).

Variable frequency drive control of evaporator fans can lead to significant reductions in refrigeration energy use, particularly in controlled atmosphere (CA) storage of fresh fruits. Typically in CA storage, the evaporator fans are operated at full speed for several weeks following the sealing of the CA storage room. The evaporator fans can then be operated at 50 percent speed while still maintaining the proper airflow within the room (Wilcox 2001). Furthermore, VFD control of evaporator fans can result in smooth temperature control within the storage room.

Variable frequency drives must be correctly sized and installed. Issues related to harmonics and motor protection require specification of appropriate input reactors, output dV/dt filters, and inverter-rated motors for successful and reliable operation. VFD systems can be operated with a computer control system or manually (Wilcox 2001).

Variable frequency drives can also be applied to condenser fans for capacity control. The rapid on/off cycling of condenser fans can result in significant variation in condensing pressure. However, application of VFD to condenser fans eliminates the rapid cycling and produces an

average condenser pressure which is smoother and lower (Wilcox 2001). The reduction in compressor energy use due to the lower condensing pressure is often times more than the fan energy savings, resulting in a net energy savings. In addition, condenser fan belt wear is reduced by using VFD control (Wilcox 2001).

Screw compressors are inefficient when operated at part-load. Thus, when using screw compressors, it is advisable to have multiple compressors which can be sequenced by the control system in order to match the load. However, there may be times when it is not possible to avoid operation of a screw compressor in the part-load or unloaded condition. In these situations, a VFD in conjunction with the compressor's conventional slide valve can be used to control the capacity of the compressor. The VFD can be used to reduce the operating speed of the compressor and the slide valve can be used to further reduce the capacity. The combination of the VFD and slide valve results in improved part-load performance as compared to only the slide valve (Wilcox 2001).

There are numerous opportunities for refrigeration system energy efficiency in new construction projects. It is suggested that high-efficiency, larger condensers be specified, thus saving both compressor and condenser energy. Rather than specifying a few large compressors, it is suggested that a diverse selection of compressors be specified. The diverse selection of compressors can more readily be sequenced by the control system to match the refrigeration load. If the refrigeration load varies significantly throughout the year, such as the case of fresh fruit storage, a combination of screw compressors and reciprocating compressors can be beneficial. The screw compressors are used to handle large loads (during harvest) and the reciprocating compressors are used to handle smaller loads (during the holding season). VFD costs can be 20 percent to 50 percent lower during new construction as compared to retrofit. Also, specify premium efficiency motors for new construction projects (Wilcox 2001).

In storage areas, metal halide lighting can be installed or retrofit with bi-level lighting. A single fixture or group of fixtures can be controlled by a motion detector. When no activity is seen for several minutes, the fixture dims. A typical 400 watt metal halide fixture may draw 465 Watts during normal operation and only 180 watts to 200 watts during dimmed operation. When motion is detected, the fixture immediately increases light output without the delay common to the initial start-up of metal halide or other high-intensity discharge fixtures (Wilcox 2001).

Storage areas are prone to significant infiltration loads. Doors are left open, or strip curtains are damaged to the point of reduced effectiveness. Fast-acting doors can be installed in these situations to reduce infiltration.

7.3 Operating Strategies

7.3.1 Reduction of Refrigeration Load

Reduce infiltration of warm, moist air into cold store (IIR 2009):

- Air locks
- Fast-acting doors
- Air seals

- Reduce number of door openings and the duration of openings
- Strip curtains
- Refrigerate and/or dehumidify loading areas
- Positive pressure in loading areas

Reduce Heat Transmission and Solar Radiation

- Proper insulation thickness
- Effective vapor retarders
- Eliminate thermal bridges in building construction
- Use light colored, reflective roofing

Minimize heat sources (motors, personnel, lighting)

- High efficiency motors
- Variable speed fan motors
- High efficiency lighting
- Turn off equipment when not in use

Products

- Incoming product should be at or near the storage temperature
- Do not store product in the loading area longer than necessary

7.3.2 Floating Head Pressure

In many refrigeration systems, the compressor discharge pressure, or head pressure, is maintained at a fixed, high level to ensure safe and reliable operation over a range of outdoor temperatures. Maintaining a high head pressure ensures the following:

- Liquid refrigerant from the condenser will not flash to vapor prior to reaching the expansion device
- Evaporative condensers will operate at a high temperature so that they will not freeze during very cold weather
- An adequate pressure differential will exist across the expansion device.

However, a system operating with a fixed head pressure is typically designed for outdoor temperature conditions that are exceeded only 2 percent of the time. Thus, under typical operating conditions, in which the ambient temperature is usually much less than the design temperature, the compressors are working harder than required to maintain the unnecessarily high head pressure. This results in lower refrigeration system efficiency, particularly during the colder seasons.

To increase refrigeration system efficiency, the head pressure can be allowed to "float" with the outdoor ambient conditions. For systems with evaporative condensers, as the outdoor wet-bulb temperature decreases, the head pressure can be allowed to decrease, thus resulting in less compressor work and increased refrigeration system efficiency. It should be noted that a

minimum head pressure must be maintained so that the expansion device functions properly (Brownell, Klein, and Reindl 1999).

In a fixed head pressure control scheme, a single set-point head pressure is maintained regardless of the system load by controlling the condenser fan operation. The scheme could be as simple as turning the condenser fans on and off to maintain a fixed head pressure. A floating head pressure control strategy allows the head pressure to float based on the heat rejection load and outdoor conditions with the condenser fans operating at maximum flow. A minimum head pressure is required to ensure that there is stable refrigerant flow through the expansion devices, sufficient pressure for hot-gas defrost, and operation of screw oil coolers. If the head pressure drops to the minimum value, the condenser fans are modulated to maintain the minimum head pressure (Manske, Reindl, and Klein 2001).

The total compressor and condenser fan power demand is a function of two opposing effects. If the head pressure set-point is increased, the condenser fans must run less or at lower speed, resulting in a savings in condenser fan energy. However, increasing the head pressure set-point increases the compressor discharge pressure and requires more compressor power for a given refrigeration capacity (Manske, Reindl, and Klein 2001).

7.3.3 Improving Refrigeration System Efficiency

Compressors (IIR 2009):

- Determine whether 1-stage or 2-stage compression is required based on pressure ratio
- Divide the compressor system into multiple temperature levels
- Use dedicated hot-gas compressors
- Avoid compressor part-load operation and frequent start-stop cycles
- Match compressor capacity to refrigeration load
- Use high efficiency compressor motors
- Screw compressors are more efficient than reciprocating compressors in the low stage.
 Conversely, reciprocating compressors are more efficient than screw compressors in the high stage.

Evaporators:

- Provide adequate refrigerant flow
- Maintain suction temperature at the highest acceptable level, based on the ambient temperature and/or production requirements
- Size evaporators for a temperature difference of 5°C–10°C (9°F–18°F) between the air and evaporator
- Ensure proper air circulation and distribution within the storage room and avoid short-circuiting
- Use high efficiency, variable speed fan
- Defrost only when required and use the shortest possible defrosting period

• Use hot-gas defrost rather than electric defrost

Condensers:

- Operate at the lowest condensing pressure as possible
- Size evaporative condensers for a temperature difference of 10°C (18°F) between the saturated condensing pressure and the wet bulb air temperature.
- Locate the condenser in an area with good air circulation and away from heat sources
- Utilize heat recovery for heating of water or under-floor heating
- Subcool the high pressure liquid refrigerant

Piping Systems and Valves:

- The pressure drop in discharge and wet suction piping should be approximately 1°C to 2°C (1.8°F to 3.6°F) per 10 meters of equivalent pipe length.
- Avoid risers in the piping system
- Use valves with low pressure drop, such as ball or butterfly valves
- Use appropriate insulation thickness on piping.

Maintenance:

- Regularly check the set points of regulating devices
- Avoid moisture in the refrigeration system. A maximum of 1 percent to 2 percent moisture in ammonia is acceptable.
- Use automatic air purgers to vent non-condensable gases from the system
- Maintain a log book of operating conditions, maintenance, malfunctioning equipment, operating hours for compressors, oil and refrigerating accounting, etc.
- Utilize computerized monitoring of operating conditions
- Change the oil in the system on a regular basis

7.4 Waste Heat Recovery in Industrial Refrigeration

Heat recovery, particularly for food processing facilities, is popular. Potential applications for using waste heat from an industrial refrigeration system include under-floor heating as required for freezers, cleanup water pre-heating, domestic water heating, boiler makeup water heating, and space heating (for both temperature and humidity control) (Reindl and Jekel 2007).

Many systems use hot compressor discharge gas for under-floor heating (using glycol), boiler makeup water, or plant cleanup water (Wilcox et al. 2007). The greatest opportunity to recover heat is through a desuperheater, where water can be heated as high as 100°F to 120°F in a circulating loop. Unfortunately, about 10 percent or less of total compressor heat rejection is superheat, so the total heat (Btu's) available for recovery is limited.

If a condensing heat exchanger is installed, water temperature is limited to the condensing temperature which, at 90 psig for ammonia, is only 58°F. Although most of the total rejected compressor heat is released in condensing, the quality of the heat recovery is limited by

saturated condensing temperature. In this case, the water could not be heated higher than the 58°F temperature of the condensing ammonia.

The economics of heat recovery often depend on the relative costs of electricity and natural gas or other fossil fuels. In some situations, it may be cost-effective to operate at elevated discharge pressure to increase heat recovery. In most cases, however, the energy cost savings from reduced condensing pressure outweighs the savings afforded by increasing heat recovery. In addition, any analysis should include the effect on compressor energy of the pressure drop on the ammonia side of the heat exchanger.

In some multi-compressor applications, one or more compressors can be operated at increased discharge pressure to act as heat pumps. In this case, heat recovery from the refrigeration system may be cost-effective, because compressor heat pumps can produce water temperatures up to 85°F or 90°F.

Several locations within an industrial refrigeration system are candidates for heat recovery, including oil cooling/heat rejection from screw compressors, head cooling in reciprocating compressors, and the high-stage discharge gas stream of reciprocating and screw compressors (Reindl and Jekel 2007).

The heat rejected through a water- or glycol-cooled oil cooler is a good candidate for energy recovery. In the oil cooling heat exchanger, hot oil from a screw compressor's oil separator enters at a temperature near the discharge gas temperature, typically between 71°C to 85°C (160°F to 185°F). The oil is then cooled in the oil cooling heat exchanger to around 54°C (130°F). Assuming a cooling fluid inlet temperature of 13°C (55°F), the cooling fluid could exit the oil cooling heat exchanger at a temperature of around 43°C (110°F). Thus, the temperature of the oil results in waste heat with a moderate quality which could be used for various applications such as under floor heating, domestic water heating and space heating.

There are many situations in which heat recovery is economical, and many others in which it is not (Stoecker 1996). The decision of how and even whether to use heat reclaim can be a tricky one that is based on:

- Relative fuel costs:
- How much of a capital investment is required;
- How much operating cost will be saved;
- Whether the timing of the availability and requirement for heat are coincidental;
- The temperature level of the rejected heat and the temperature level of the heating need.

7.5 Evaporator Defrost

7.5.1 Flexible Defrost

It is advantageous to use a flexible defrost strategy rather than a fixed strategy which is based on a worst case scenario, such as that which might occur during a hot and humid summer day. For example, during the winter, cold outdoor air contains about 30 percent of the moisture that it could hold on a warm summer day. In addition, the rate of air flow through an open doorway

is slower in the winter since the infiltration rate into a cold storage facility is proportional to the temperature difference between the inside and outside air temperatures. Therefore, for maximum energy efficiency, the frequency and length of defrost cycles should be seasonally based, so that defrost cycles occur less often and with shorter duration during the winter as compared to the summer (BFFF 2009).

7.6 Optimize Commercial Electrical Energy Utilization

7.6.1 Power Factor

In a study performed by Zhang and Groll (2000), they found that an important method for improving the efficiency of refrigerated storage facilities, namely, improving the facility's power factor, was often overlooked. Most of the electric motors used in industrial refrigeration plants are AC induction motors. The current of an AC induction motor has two components: the active component and the reactive component. The active component is responsible for the torque and work produced by the motor. The reactive component creates a rotating magnetic field that does not perform useful work, but is required to excite the motor to create the rotating magnetic field. The power factor is the ratio between the real power (measured in watts or kW) and the apparent power (the product of the voltage times the current, measured in volt-amperes or kVA). The power factor is expressed as a fraction from zero to one, with a power factor of one representing a purely resistive load and a power factor of zero representing a purely inductive load.

When a motor is operating at no load, the energy absorbed by the motor is equal to the motor inefficiencies, and thus, the active component is small compared to the reactive component and the power factor is very low (~10 percent). At full load, the active component is at its maximum, and for a most three-phase motors, the power factor is typically between 70 percent and 95 percent. A high power factor is desirable because it implies that the reactive component is low and the motor is operating more efficiently (Zhang and Groll 2000).

An electric utility company must supply the apparent power, which consists of the active and reactive powers, to its customers. Thus, most utilities penalize consumers that have power factors below some threshold level, typically 85 percent to 95 percent. Most electric motors in refrigeration plants are operating at part-load because the motors are oversized for the application. Furthermore, modern refrigeration compressors are commonly equipped with unloading devices so that when mass flow rates are low, the compressors are unloaded and the compressor motors are lightly loaded. Thus, it has been found that the power factor for refrigerated warehouses typically ranges from 60 percent to 80 percent (Zhang and Groll 2000). Hence, not only are the electric motors being operated inefficiently at part load, but there is also an economic benefit to the facility owner to please the electric utility company by raising the power factor of the facility.

Power factors can be increased by installing capacitors at any point in the electrical system, with the improved power factor occurring between the point of application of the capacitors and the power source. The most economical installation for a particular refrigerated storage facility will depend upon the electric utility rate structure. Zhang and Groll (2000) show that installation of

capacitors may result in a payback time of less than one year of operation, assuming a typical installation cost for electric capacitors in the range of \$20 to \$30 per kVA of reactive load (or kVAR).

7.6.2 Power Factor Correction

There are two kinds of power factor, "displacement" and "distortion". This description applies to displacement power factor, which is more commonplace, and its correction is rather simple. Should significant harmonics be present, then distortion power factor becomes important and the methods of mitigation described herein may not be viable.

Power factor correction is the process of providing needed reactive energy locally at the load rather than suffer the disadvantages of its travel through the electric system where it provides no benefit to the utility or to the consumer. Balanced loads have equal electrical potential differences and currents for each phase. As balanced multiphase loads are analogous to multiple single-phase loads, power factor and its correction applies equally well to single-phase circuits as well as multi-phase circuits (3-phase, 6-phase, etc.).

As shown in Equation (20), power Factor, P_f (dimensionless), is the ratio of real power, P (W), to apparent power, S (VA).

$$P_f = \frac{P}{S} \tag{20}$$

Power factor is akin to mechanical efficiency. Although not identical, it does measure the ratio of real power that can do work, *P*, to total apparent electrical power absorbed, *S*. Obviously if such a ratio exists, there must be a difference between *S* and *P* and indeed, there is.

The difference is reactive power, Q (VAR). VAR is an acronym for Volt-Ampere Reactive. Any circuit that is inductive or electronically switched requires reactive power. Sources of reactive power include power electronics circuits, generators, some special motors and capacitors. The purpose for the reactive power, although it does no real work itself, is to provide the reactive energy required to support the magnetic fields developed by the coils of inductive devices. The magnitudes of S, P, and Q are related as shown in Equation (21).

$$S^2 = P^2 + Q^2 (21)$$

Graphically, S, P, and Q are related as shown in Figure 39.

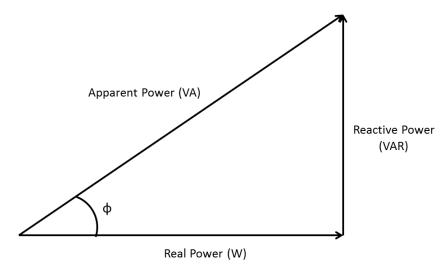


Figure 39: Relationship Between Real Power, Apparent Power and Reactive Power.

As a simple example of reactive power, consider a hair dryer, for instance. The hairdryer's nameplate states: "Hairdryer, 120 Vac, 1,000 Watts, 10 Amperes, 50/60 Hz". The apparent power, S, required by the hairdryer is the nameplate voltage (120 V) multiplied by the nameplate amperage (10 A) and the result is S = 1200 VA. This is the full voltage that may be applied to the hairdryer times its full current. There can be no more power applied to this hairdryer and be within its nameplate rating and so this is the total apparent electrical power to be absorbed by the hairdryer. You will notice that the nameplate power is only 1,000 W. This is the real power, P.

Where is the missing quantity that makes for the difference between the apparent power, S, and the real power, P? It is the reactive power, Q. In this example, Q = 663 VAR. Note that Q is not 200 VAR, the algebraic difference between S and P, because the reactive power, Q, and the real power, P, are 90 degrees apart electrically, as shown in Figure 40.

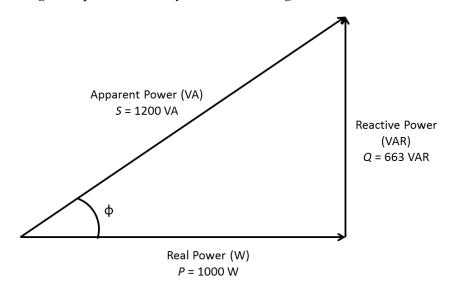


Figure 40: Real Power, Apparent Power and Reactive Power for the Hairdryer Example.

From Equation (21), *Q* may be found as follows:

$$Q = \sqrt{S^2 - P^2} \tag{22}$$

For this hairdryer example:

$$Q = \sqrt{1200^2 - 1000^2} = 663 \text{ VAR}$$
 (23)

Thus, even hairdryers require reactive power.

The recipients of this reactive power are motors, transformers, generators, power electronics circuits, wires and almost any circuit that contains these devices. Approximately 97 percent of all devices are inductive and require reactive power. Some devices, like synchronous motors/generators and power electronic devices, both absorb and deliver reactive power.

The important point is, if a refrigerated facility has devices that require reactive energy and almost every facility does, the required reactive energy has to travel from the utility, through the utility's system, into the refrigerated facility, through the facility's system and to the loads. The entire path of the reactive power demanded by the facility's loads produces real energy loss for all concerned. The reactive energy does no load any good until it arrives at the load. It is the ferrying of the reactive power that increases the loss. Although this power is not in phase with the real power doing the work, as shown in Figure 41, it most definitely contributes to the ampere sum. This increased current adds to the heating effect of the wire and the equipment, the burden on the utility, the burden to the facility's electric bill and most definitely the reduction of the facility's power factor.

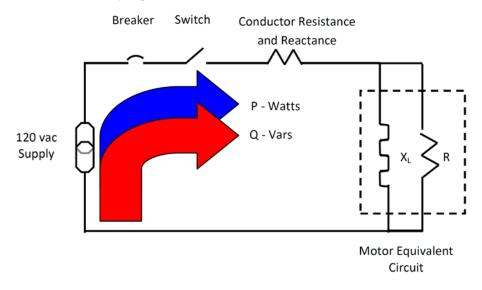


Figure 41: Real Power and Reactive Power Supplied from the Utility.

As shown in Figure 42, local power factor correction, through the use of power factor correction capacitors, provides the reactive energy locally. This local correction reduces the reactive power that the utility has to provide and may possibly reduce the refrigerated facility's utility

bill, especially if a power factor penalty applies. This local power factor correction also reduces the reactive energy that the utility's distribution system has to ferry and again may result in a possible reduction in the facility's utility bill. Furthermore, if the power factor correction capacitors are mounted close to the load, local power factor correction also reduces the ampere capacity burden within the refrigerated facility's electric distribution system which also reduces the real energy portion of the facility's utility bill.

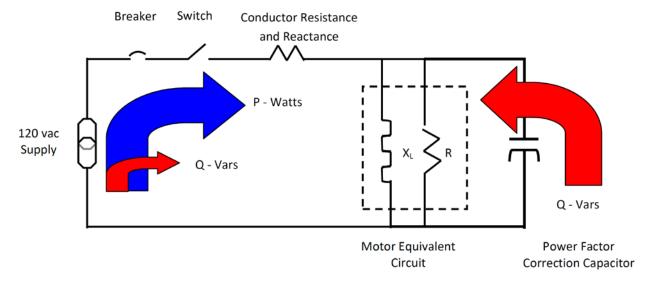


Figure 42: Power Factor Correction Using Capacitors.

Finally, if it is possible to connect the capacitors close to the motors, the amount of resistance heating, I^2R , in the wires between the motor and the utility's service supply is minimized. This will directly reduce the refrigerated facility's utility bill.

Once the National Electrical Code (NFPA 2002c, 2002a) limitations for installing the capacitors are determined and calculated, the financial effect may be determined. If a significant harmonic presence is not found, the only question is whether there is sufficient loss or penalties in the refrigerated facility's utility contract to offset the cost of installing the required power factor correction equipment within a reasonable payback period. Figure 43 shows examples of typical power factor correction capacitors.

7.6.3 Demand Response Programs

Demand response programs offered by electric utility companies provide a mechanism for refrigerated storage facility operators to manage their consumption of electricity in response to supply conditions. A variety of events, such as storms, heat waves, and power plant outages, can affect the supply and demand for electricity. When demand for electricity is high and supply is low, power interruptions can result. Demand response programs offer incentives to businesses to voluntarily reduce their electricity consumption during occasional periods when demand could be higher than supply (Pacific Gas and Electric Company 2010).



Figure 43: Typical Industrial Power Factor Correction Capacitors.

Electric utilities provide tariffs and incentives to customers in an effort to encourage customers to shed or shift their electrical load during periods when the electrical grid is operating near its capacity. Demand response is dynamic and event-driven and customers modify their end-use electric loads in response to dynamic pricing and grid reliability information.

Based on the next day's weather forecast and projected system load, electric utilities will typically send a notice 24 hours prior to a pending demand response event to its demand response program participants. Customers then implement their demand response program which could be manual, semi-automated or fully-automated. A manual demand response consists of manually turning off equipment or changing equipment set points. Semi-automated demand response consists of pre-programmed load shedding or shifting strategies initiated by an individual via a central control system. A fully-automated demand response requires no human intervention and is initiated by the facility's Energy Management Control System (EMCS) which implements pre-programmed load shedding and shifting strategies (Motegi et al. 2007).

Refrigerated storage facilities which incorporate computerized control technologies for energy efficiency and load management can easily implement automated demand response programs. The computerized controls provide access to real-time data required for automated demand response (Lekov et al. 2009).

During periods of peak utility load, the electrical demand of refrigerated storage facilities can be reduced by load shedding and load shifting. Load shedding strategies reduce the facility's electrical load and load shifting strategies move the electrical load to off-peak hours.

Nonessential electrical equipment in a refrigerated warehouse may be turned off to shed load during a demand response event. Increasing temperature set points will reduce compressor loads. The amount of insulation within the facility walls and roof will dictate the duration

during which compressor load can be reduced while maintaining proper storage temperatures within the facility (Lekov et al. 2009).

Lighting in non-essential areas can be turned off or dimmed during demand response events. As an added benefit, reduced lighting will also result in less heat load in the cold storage space, thus reducing the refrigeration load.

In a study of a refrigerated warehouse in Livermore, CA, it was found that about 25 percent of the facilities electrical load could be reduced by turning off HVAC systems in non-essential areas and increasing temperature set points in office spaces (Demand Response Research Center 2009).

During demand response events, variable frequency drives may be used to operate compressors and condenser and evaporator fans at the minimum capacity required to maintain proper storage conditions.

Prior to a demand response event, the products in the refrigerated storage space can be precooled to a temperature lower than the normal storage temperature. Thus, during the demand response event, the refrigeration equipment can be turned off and the temperature of the products increases slowly. The effectiveness of pre-cooling depends upon the thermal mass of the stored product. In addition, loading and unloading operations, use of forklifts and use of lighting should be minimized in the storage space in order to reduce the thermal load in the space and to maintain the storage temperature within acceptable limits. Prior to implementing a pre-cooling load shifting strategy, the product should be tested to ensure that it is not damaged during the temperature fluctuations which occur. In addition, lowering the temperature in the refrigerated space places an additional demand on the compressors, and thus, the refrigeration system must be capable of delivering a higher refrigeration load during the pre-cooling process (Lekov et al. 2009).

Battery charging loads can be shifted to off-peak periods so as not to coincide with demand response events. In addition, if electric defrost is utilized in the refrigerated storage facility, automatic evaporator defrosting could be disabled during demand response events to prevent evaporator defrosting during the DR event (Lekov et al. 2009).

7.6.4 Open Automated Demand Response

Open Automated Demand Response (OpenADR) is a set of continuous and open communication signals and systems provided over the Internet to allow facilities to automate their demand response with no "human in the loop (Lekov et al. 2009)."

Refrigerated warehouses have the potential to benefit from the implementation of demand response and energy efficiency strategies. Many refrigerated warehouses have computerized control systems to monitor and control the performance of the refrigeration system components. Facilities which have implemented energy efficiency measures and have centralized control systems are well-suited to shift or shed electrical loads in response to financial incentives, utility bill savings, and/or opportunities to enhance reliability of service. Control technologies installed for energy efficiency and load management purposes can often be adapted for open

automated demand response (OpenADR) at little additional cost. Supervisory control and data acquisition (SCADA) systems are measurement and control systems that gather real-time data from remote locations and control equipment and operating conditions at the supervisory level (Lekov et al. 2009).

Supervisory control and data acquisition (SCADA) systems consist of the following components (Lekov et al. 2009):

- Master terminal unit (MTU): system data is stored and operators manage automation activities via Human-Machine Interfaces (HMI). SCADA collects and processes data, issues alarms and controls equipment
- Remote Terminal Units (RTU): microprocessors that gather data from sensors and deliver the data to the SCADA
- Programmable Logic Controllers (PLC)
- Proportional Integral Derivatives (PID)

Centralized control systems, such as SCADA, are ideal for the application of an automated demand-response system. The integration of individual equipment controls and locally distributed controls into SCADA allows the automated demand-response system to interact with a single control system instead of multiple systems, thus creating a cost-effective and reliable base for OpenADR implementation (Lekov et al. 2009).

7.6.5 Electrical Load Shifting

For a refrigerated storage facility which stores frozen foods, it may be advantageous to use the food products as a means of storing thermal energy, thus reducing energy costs (Becker and Fricke 2005). During periods when the cost of electricity is low, the temperature of the storage space and the food products may be reduced to a lower than required level. Then, during times of peak electrical demand, when the cost of energy is high, the temperature of the storage room and the products may be allowed to rise to the required storage temperature, thus, minimizing the power required to operate the refrigeration equipment during the peak demand periods. This technique, however, must be approved by the owners of the food products and be closely supervised and monitored to assure that food quality and/or food safety is not impaired.

As mentioned above, use of nonessential electrical equipment in a refrigerated warehouse may be shifted to periods when the cost of electricity is low. For example, battery charging loads could be shifted to off-peak periods, thus reducing energy costs.

7.7 On-Site Electrical Energy Generation

7.7.1 Solid Oxide Fuel Cells

Solid oxide fuel cell technology may provide refrigerated facility owners and operators the option to obtain their electricity from a clean energy source rather than from a coal-fired power plant. A solid oxide fuel cell consists of an electrolyte which is sandwiched between a cathode and an anode. The fuel cell produces electrical power through a chemical reaction involving air and fuel. On the anode side of the fuel cell, reformed fuel is produced by a reaction between steam and a fuel, such as methane, resulting in hydrogen and carbon monoxide. Oxygen ions

are formed on the cathode side of the fuel cell from warm air which enters the fuel cell. The reformed fuel attracts the oxygen ions, forming water, carbon dioxide and electricity. The fuel cell must operate at high temperature (typically above 800°C) in order to function, however the heat generated by the chemical reaction is sufficient to sustain operation. Figure 44 through Figure 47 depict the operation of the solid oxide fuel cell (Bloom Energy Corporation 2010).

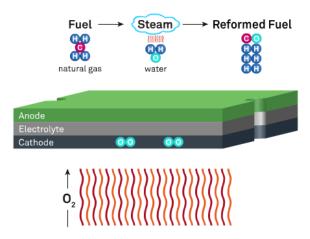


Figure 44: Warm Air Enters the Cathode Side While Fuel and Steam Combine on the Anode Side to Produce Reformed Fuel.

Source: (Bloom Energy Corporation 2010)

Fuel Steam Reformed Fuel

Inatural gas Water

Anode

Electrolyte

Cathode

Figure 45: Oxygen from the Air on Cathode Side and Hydrogen and Carbon Monoxide from Reformed Fuel on Anode Side.

Source: (Bloom Energy Corporation 2010)

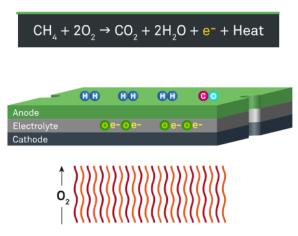


Figure 46: Hydrogen and Carbon Monoxide Attract the Oxygen Ions.

Source: (Bloom Energy Corporation 2010)

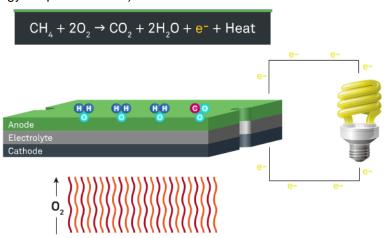


Figure 47: Oxygen Ions Combine with Hydrogen and Carbon Monoxide to Form Water, Carbon Dioxide, Electricity and Heat.

Source: (Bloom Energy Corporation 2010)

7.7.2 Solar Electric Systems

The roof of a single story refrigerated storage facility of 50,000 ft² or greater provides an excellent opportunity to utilize roof-mounted photovoltaic cells to generate electricity for the facility.

Solar electric systems (also known as PV systems) use the direct conversion of sunlight to direct current (DC) electricity(LANL 2002). The four major types of PV cells in order of highest to lowest performance and cost are single crystal, polycrystalline, thin film, and amorphous silicon cells. The cells have a long life and are almost maintenance free. The cells are assembled into modules and the modules are connected into arrays. The type of cell connection determines the voltage and current of the array. The power generated by a PV array is instantaneous direct current while the sun shines. Most systems include alternating current (AC) inverters and some include batteries for storage.

PV systems may be stand-alone or utility-grid-integrated. A stand-alone system is applicable to remote locations that are at least one-quarter mile from utility connections. For stand-alone systems, a fuel generator and/or batteries may be used to provide electricity during periods of insufficient solar radiation. A grid-integrated system supplements utility power. In buildings having an uninterruptible power supply (UPS) system, the PV system can charge the UPS battery bank and supply supplemental power to the building.

PV arrays may be mounted directly on the building or on nearby racks. Building integrated PV modules are available as roofing tiles, shingles, standing seam metal roofing, spandrel panels, or as partially transparent shading elements. The building site might incorporate PV arrays as shading devices for parking areas, pedestrian walkways, or outdoor gathering spaces. PV systems are still quite expensive when grid power is available, but improvements in efficiencies, manufacturing, and storage systems promise to reduce the total system cost of future PV installations. It may be desirable to plan building surfaces with proper solar access and wiring access points for a future PV system. PV systems sometimes make economic sense when very high-quality, uninterruptible power is needed

7.7.3 Wind Energy

At study was conducted to determine the feasibility of combining wind energy with refrigerated warehouse operation. The concept involves utilizing wind energy, when available, to store thermal energy within the refrigerated warehouse. During periods of high wind energy, the temperature within the refrigerated warehouse can be lowered using the "excess wind energy", thereby reducing the future cooling demand. When wind power availability is low, the temperature within in the refrigerated warehouse can be allowed to rise. As part of the study, a controller was devised to forecast when thermal energy within the refrigerated storage facility could be stored and released based on the availability of wind power and the price of electricity from the power grid. Simulation of the control system was performed but actual implementation of the control system in a refrigerated storage facility was not performed (Cronin, Bindner, and Zong 2008).

7.8 Training

The basic objective of a personnel training program is to develop qualified technicians who have the knowledge to operate and maintain building systems in accordance with design intent and procedures (ASHRAE 2011a; IIR 1990). Training is very important for the safe and effective operation of a warehouse or any plant. The training program should furnish a thorough understanding of all equipment, components, systems, and their operation and should generally include the following topics (ASHRAE 2011a; IIR 1990):

- Operation procedures for all modes of operation.
- Description, capabilities and limitations of all systems.
- Procedures for dealing with abnormal conditions and emergency situations.
- Acceptable tolerances for adjustments in all operating modes.

- Use of operation manuals.
- Use of maintenance manuals.
- Use of control systems.

Cold storage facilities utilizing ammonia refrigeration systems containing more than 10,000 lb (4536 kg) of ammonia are required to conform with OSHA 29CFR1910.119, "Process Safety Management of Highly Hazardous Chemicals" (OSHA 2002). This code specifically states that any employee who is involved in operating an ammonia refrigeration system containing more than 10,000 lb (4536 kg) of ammonia shall be trained in an overview of the refrigeration system and in its operating procedures. This mandatory training shall include emphasis on the specific safety and health hazards, emergency operations including shutdown, and safe work practices applicable to the employee's job tasks. In addition, the code specifies that refresher training shall be provided at least every three years, and more often if necessary, to each employee involved in operating an ammonia refrigeration system containing more than 10,000 lb (4536 kg) of ammonia to assure that the employee understands and adheres to the current operating procedures of the refrigeration system.

A detailed training program for industrial refrigeration systems operators and technicians is available from the Refrigerating Engineers and Technicians Association (RETA). In addition, the International Institute of Ammonia Refrigeration (IIAR) and RETA have begun collaborating on a joint project to develop uniform guidelines that define the information that well-trained operators should be aware of.

CHAPTER 8: Life Cycle Cost Analysis

8.1 Total Cost

The total cost of owning and operating a refrigeration system consists of capital purchase, cost of maintaining it in reasonable working order, cost of repairing when it suffers a breakdown, cost of electricity for the system and associated devices and other utility costs, such as the cost of water for an evaporative condenser. It is also necessary to consider the cost of ultimate replacement at the end of the system's useful life (Pearson 2007).

8.2 Life Cycle Costing

A properly designed refrigerated storage facility must be capable of providing the required storage environment in a cost-effective manner. In order to design a cost-effective refrigerated storage facility, both owning and operating costs must be considered. In some cases, comparisons of design and asset alternatives have been based solely upon initial capital costs. However, the operating costs of a refrigerated storage facility are substantial, consuming the equivalent of its capital cost every several years. Thus, the life cycle costing process should be used to assess alternatives, both during the design and operation of the facility (Becker and Fricke 2005).

The life cycle costing process accounts for all of the costs associated with the refrigerated storage facility, including fabrication, acquisition and installation, operation, maintenance, and refurbishment costs. Life cycle costing can be used to sum all the costs of alternatives over their life period and enable an evaluation on a common basis for the period of interest, usually using discounted costs. This enables decisions on acquisition, maintenance, refurbishment or disposal, to be made in the light of full cost implications. Life cycle costing is essential to the asset management process as an input to the evaluation of alternatives via economic appraisal, financial appraisal, and value (NSW Government Asset Management Committee 2001).

The costs which are used to determine the life cycle cost include the following:

- Ownership costs: income taxes, property taxes, insurance, lease, replacement cost, depreciation of buildings and equipment.
- Operating costs: electrical energy, water, fuel gas, solid waste disposal, waste water disposal, operating labor and benefits, operating supplies, outsourced operational resources.
- Maintenance costs: maintenance parts and supplies, maintenance labor and benefits, outsourced maintenance work and contracts.

Life cycle costing can be carried out during any or all phases of an asset's life cycle. It can be used to provide input to decisions regarding asset design, manufacture, installation, operation, support and disposal. Life cycle cost analysis enables the creation, operation and disposal costs of an asset to be monitored throughout its life to enable accurate and timely decision-making as

to how these costs can be minimized (ASHRAE 2011a; NSW Government Asset Management Committee 2001).

8.3 Life Cycle Cost Analysis

Life cycle cost analysis is a method to evaluate capital investment purchasing decisions. Life cycle cost analysis accounts for initial, ongoing, and future costs, and the value of future benefits of an investment, typically over the life of a project (Wilcox et al. 2007). It facilitates comparison of alternative systems based on the differences between their respective initial costs, operating costs (including energy savings), and maintenance costs over their lifetimes. To achieve this, each alterative project is placed on the same economic footing, and the cost of capital over time is considered. The total life cycle cost in current dollars, *LCC*, is calculated as follows:

$$LCC = Cost_{Initial} + Cost_{Operation} + Cost_{Maintenance} - Value_{Benefits} - Value_{Salvage}$$
 (24)

where *Cost* mitial is the initial cost in current dollars, *Cost* operational is the operating costs over the project life, discounted to current dollars, *Cost* Maintenanceis is the maintenance costs over the project life, discounted to current dollars, *Value* Benefits is the value of any project benefits over the project life, discounted to current dollars (this could include things like production rate, product quality, or labor productivity), and *Value* is the salvage or resale value of the project (if any) at the end of its life, discounted to current dollars.

Many of these items are straightforward, but because of several components of the life cycle cost are spread over many years, they must be converted to comparable units of cost, usually current year dollars. This is done by "discounting," which accounts for things like inflation (or deflation) and depreciation (or appreciation) (Wilcox et al. 2007).

To determine which alternative project is the most economically attractive, the life cycle cost of each alternate project should be determined and compared. The alternative with the lowest life cycle cost is usually the most economically desirable. Life cycle cost analysis allows the alternative project with the lowest overall cost to the organization over the life of the project to be determined.

In practice, life cycle cost analysis can be complex when it accounts for the effects of things like inflation, taxes and tax credits, escalation of energy costs, and system components with different economic lifespans.

In summary, a life cycle cost analysis involves converting all project costs and benefits, initial and future, into current dollars, comparing each project alternative, and selecting the one with the lowest total cost. Often, the project with the lowest total cost is not the project with the lowest initial cost, thus performing a life cycle cost analysis can be justified (Wilcox et al. 2007).

8.4 Life Cycle Cost Analysis Software

The U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) Information Resources Center online at www1.eere.energy.gov/femp/program/lifecycle.html offers a free download of the *Building Life Cycle Costing Software*.

Numerous computer models are available to perform economic analysis, ranging from simple spreadsheet macros to more complex and comprehensive, menu-driven computer programs. Examples include Building Life-Cycle Cost (BLCC) (NIST/DOE), Life Cycle Cost in Design (LCCID) (USA-CERL/USACE) and PC-Econpack (USACE).

CHAPTER 9: Retrofitting

For existing refrigerated storage facilities, the energy efficiency can be improved by adding insulation, replacing old motors with more efficient motors, minimizing the pressure difference between the compressor and the condenser, utilizing automatic closing doors and using improved electro-mechanical control systems (Duiven and Binard 2002).

There are a significant number of refrigeration systems that are greater than 10 years old with substantial remaining service life. Many of these systems have standard electro-mechanical controls (e.g., pressure switches) and manual control. These systems are typically set up for minimal hands-on interaction and worst-case operating conditions, resulting in low system efficiency. Often, the systems are operated with low suction pressure, high head pressure and little or no evaporator fan control. Although this method of operation may provide adequate control of room temperature, energy use is excessive and documentation of temperatures, pressures and other key information is infrequently, if ever, gathered (Wilcox 1997).

In upgrading these older refrigeration systems, four primary technologies are considered:

- Computer Control
- Compressor Unloaders
- Liquid Pressure Amplifiers
- Variable Speed Drives

Computer control can be considered the "backbone" of any system upgrade, particularly when energy efficiency is targeted. The control system provides the modern user interface necessary for pressure management and fan control, both on evaporator coils and condensers. And in some cases, the control system can actually optimize operations, looking to push system pressures to allowable extremes while maintaining target room temperatures (Wilcox 1997).

Most of the aging reciprocating compressors have manually-adjusted cylinder unloaders with a range of approximately 10 to 15 psig in suction pressure over which the compressor moves from fully unloaded to fully loaded. With two or more compressors, these loading ranges are commonly staggered. The result may be a 20 to 40-psi range of suction pressures between the first compressor starting to load and the last compressor becoming fully loaded. Since the last compressor is commonly set to come on within the acceptable target suction pressure, the result is an average suction pressure well below that required, particularly during light system loads. This low suction pressure means reduced compressor capacity and increased compressor energy consumption. Most reciprocating compressors can be retrofit with electrically activated unloaders. Coupled with a computer control system, the unloaders can be used to maintain tight control over suction pressure (Wilcox 1997).

Liquid pressure amplifiers (LPAs) are designed to circumvent the limited capabilities of R-22 systems. With minimal latent heat (relative to ammonia), R-22 is highly susceptible to pressure drop and flash gas. This flash gas nearly shuts off the refrigerant flow through thermal

expansion valves (TXVs). Furthermore, typical TXVs are sensitive to pressure differential. When suction pressure rises or discharge pressure falls, TXV performance may lag due to insufficient pressure differential. The LPA pump is a small, seal-less, magnetically driven pump. This pump is installed on the liquid line between the condenser outlet and TXV. The pump boosts liquid line pressure, eliminating any flash gas. In addition, the TXV is served high pressure liquid refrigerant to ensure adequate flow rate. With LPAs installed, a system can be operated at higher suction pressures and lower discharge pressures to reduce compressor power and increase system capacity (Wilcox 1997).

Variable frequency drives (VFDs) allow induction motors, which normally operate at one speed on the 60 cycle power supplied from the utility company, to operate over a range of frequencies. Thus, and induction motor controlled by a VFD can operate at any speed between 0 percent and 100 percent (Wilcox 1997).

The performance of fans are governed by the "affinity laws", which state that airflow is proportional to fan speed and fan power is proportional to the cube of fan speed. Thus, theoretically, an evaporator fan operating at 50 percent of its full speed will provide 50 percent of its rated airflow and will require 12.5 percent of its rated power $(0.5^3 = 0.125)$ (Wilcox 1997).

The speed of computer controlled VFD evaporator fans can be reduced to some minimum setpoint (typically somewhere between 40 percent to 75 percent) when the desired room temperature is achieved. Temperature probes located throughout the storage space are used to ensure proper room conditions (Wilcox 1997).

VFD controls can be used on condenser fans in place of fan cycling for minimum head pressure control. In addition, VFD driven fans start and stop more gently, reducing wear on fan belts and pulleys (Wilcox 1997).

Although each of these technologies is proven, improper installation or inadequate design can result in problems. Specifically, LPAs should be installed following factory recommendations for proper net-positive suction head. This will ensure no cavitation at the pump inlet. In addition, VFDs should be carefully and thoughtfully applied. Issues such as motor "robustness", lead lengths, bypassing, line reactors and motor grouping should be considered by qualified personnel prior to installation.

CHAPTER 10: Commissioning and Re-commissioning

This section presents a discussion of commissioning, which ensures that the facility is constructed in accordance with the contract documents, and verifies that the facility and its systems function as intended. Re-commissioning on an annual basis is also advantageous as a means of ensuring the proper functioning and upkeep of the facility's systems throughout their useful lives. Given its importance and many potential benefits, commissioning is essential to green, sustainable, energy efficient, cost-effective operation of a refrigerated storage facility and should be included as standard practice. In addition, this section also discusses the evaluation of data from the energy accounting system and annual commissioning as a means to assess the potential benefits of retrofitting an existing facility

10.1 Commissioning

Commissioning is defined as a quality assurance process for the installation of systems in a building (ASHRAE 2011a). Commissioning is a process which ensures the quality of the installation by verifying and documenting the performance of each system as compared to the design specifications. The result of commissioning should be fully functional systems that can be properly operated and maintained throughout the useful life of the building (Becker and Fricke 2005).

The following are some of the steps in commissioning of refrigerated warehouses (IACSC 1999a):

- The refrigeration system shall be thoroughly checked for leaks prior to charging with refrigerant.
- The vapor seals shall be checked for integrity.
- The floor heating system, door threshold heaters and all trace heating shall be checked for operation.
- Lighting and emergency lighting, including movement detectors, shall be checked.
- All interior surfaces shall be cleaned and disinfected as appropriate.
- Fire detection systems, including smoke and heat detectors, shall be checked for operation.
- All doors, both manual and automatic, shall be checked for their operation.
- Refrigerant leak sensors shall be tested for proper operation.
- The refrigeration equipment start-up and storage space temperature pull-down rate plan shall be verified and then executed to ensure that thermal expansion and contraction does not become a problem.

A complete commissioning list should be prepared well in advance of the commissioning process and this list should be agreed upon by all parties involved. The size and make-up of

the commissioning team depends on the size and complexity of the project and the owner's desire to invest in quality assurance.

10.2 Water Vapor Removal

During installation, the core material of all insulation panels naturally contains water vapor which was absorbed from the ambient. Thus, when the warehouse is lowered to operating temperature, the water vapor within the insulation panels is drawn to the cold surface and to the joints; which may result in initial light frosting at the joints. If the initial insulation panel drying process is complete, the light frosting will not occur. During the commissioning process, this light frosting phenomenon should be checked (IACSC 1999a). However, it should be noted that the light frosting described above does not necessarily indicate a failure of the external vapor seal.

10.3 Documentation

10.3.1 Preventative Maintenance Plan

The performance and reliability of a refrigerated storage facility and its equipment depends upon regular, systematic, conscientious maintenance. A maintenance schedule or maintenance plan should be determined for all equipment, including the building itself (Becker and Fricke 2005).

The frequency of required scheduled maintenance depends upon various factors including operating conditions, manufacturers' recommendations, product throughput, climate, and personnel qualifications and attitude. Maintenance may be performed by facility personnel or outside contractors.

As a minimum, the maintenance plan should include periodic inspection and maintenance of the following items:

- Structure: vapor retarder, insulation, roof, walls, doors, floors.
- Product handling equipment: forklifts, conveyors, pallet racks.
- Refrigeration equipment: compressors, pumps, tanks, condensers, evaporators, fans, piping, valves, instrumentation, purgers, system oil management.
- Safety devices: fire detection devices and alarms, refrigerant leak detectors and alarms, fire extinguishing devices.

10.4 Thermographic Scans

During commissioning, an infrared thermal imaging survey, or thermographic scan, should be performed to check the thermal integrity of the refrigerated storage facility (IACSC 1999a). Another scan should be performed shortly before the expiration of the warranty period or after 12 months of operation, whichever is sooner. The purpose of the initial scan is to reveal any imperfections in the panels or gaps at the panel joints. Subsequent scans will indicate excessive moisture penetration and deterioration of the insulated envelope.

Thermographic scans not only provide a qualitative measure of the thermal performance of the insulated envelope, but also identify areas of high or low thermal emission in relation to the average thermal emission. These scans provide a valuable means of assessing the initial and continuing thermal performance of the insulated envelope.

The temperature within the refrigerated facility should be at least 30°F (17°C) below the external ambient dry-bulb temperature in order to properly identify the high or low areas of thermal emission. During the scanning process, the doors should be closed with evaporator fans and room lighting switched off. Personnel should not be allowed to enter the room during the thermographic scan. The room should be allowed to thermally stabilize for 48 hours, under the closed door conditions, before the testing is undertaken. Panels, joints, and doors should be separately subjected to thermal imaging.

CHAPTER 11: Case Studies

11.1 Energy Efficiency Case Studies

Lekov et al. (2009): Several case studies are summarized regarding energy-efficiency retrofits and demand response strategies. In a 345,000 ft² frozen food distribution center located in Livermore, California, several demand response procedures were implemented, including turning off several air handlers in the freezer, raising HVAC system set points and turning off battery chargers. It was found that these demand response strategies allowed the facility to shed approximately 25 percent of its total load while maintaining product temperatures within acceptable limits (Demand Response Research Center 2009; Lekov et al. 2009).

In a beer distribution warehouse located in Rhode Island, it was estimated that a combination of load shedding and load shifting strategies could reduce the facility's peak demand of 463 kW by nearly 160 kW during demand response events. The load shedding strategies included shedding 50 percent of the refrigerated warehouse lighting, 50 to 100 percent of hallway lighting and 20 percent of office lighting. In addition, HVAC temperature set points were raised in non-essential areas. These load shedding strategies were estimated to reduce electrical load by 50 kW. Load shifting strategies included precharging forklift batteries prior to a demand response event, pre-cooling the warehouse in order to turn off all compressors during a demand response event and disabling electrical defrost during a demand response event. These load shifting strategies were estimated to reduce electrical load by 110 kW (Lekov et al. 2009).

A 50,000 ft² refrigerated storage facility located in Gresham, Oregon, built in 1996, incorporated several energy efficiency measures. Six inch thick extruded polystyrene wall and floor insulation as well as 15 inch thick extruded polystyrene ceiling insulation were used. An oversized condenser, axial condenser fans, premium-efficiency motors, variable frequency drives for condenser and evaporator fans, and three different sized screw compressors with thermosiphon cooling were installed. In addition, fast-acting doors on the loading docks and efficient lighting were specified. Compared to a baseline refrigerated storage facility with standard design and equipment, it was estimated that the energy efficient Gresham, Oregon storage facility could save 1,140,000 kWh per year (Lekov et al. 2009).

Heaney et al (2007): Heaney et al (2007) present three case studies of the use of natural refrigerants, including the use of hydrocarbon refrigerants in small ice cream freezers and beverage coolers, the use of an ammonia/CO₂ cascade refrigeration system in a supermarket and the use of an ammonia/CO₂ cascade refrigeration system in an industrial food freezing operation.

The industrial food freezing operation consists of an automated air blast freezing tunnel as well as chilled and frozen food storage. An ammonia/CO₂ cascade refrigeration system was chosen for this facility due to environmental concerns (CO₂ has a GWP of 1) and an ammonia/CO₂ cascade system was deemed better in terms of occupational health and safety as compared to an ammonia-only system. In addition, since CO₂ would be distributed to the food freezing and

food storage areas rather than ammonia, any leak of refrigerant would not affect the quality of the processed or stored food. Other advantages included higher system efficiency with the ammonia/CO₂ cascade system as compared to an ammonia-only system and the CO₂ portion of the system operates under positive pressure, and thus, air and other contaminants cannot easily enter the system. In contrast, low temperature ammonia systems operate at below atmospheric pressure, leading to potential contamination of the system (Heaney et al. 2007).

The ammonia/CO₂ cascade refrigeration system significantly reduced the ammonia refrigerant charge as compared to an ammonia-only refrigeration system. It was estimated that the charge for an ammonia-only system would be about 90 percent higher than the cascade system. The cascade system also incorporated a plate and shell type cascade condenser which, due to its good heat transfer characteristics, aids in minimizing the ammonia charge (Heaney et al. 2007).

11.2 Energy Efficiency in Produce Processing and Cold Storage Facilities

In a study performed by Hackett et al. (2005), energy audits were performed on seven fresh fruit and vegetable processing/storage facilities in California and potential measures for energy and cost savings were identified.

According to the US Census Bureau, there were 235 frozen fruit, juice, and vegetable processing facilities in the US in 2002. These 235 facilities consumed approximately 2.9 billion kWh of electricity and had energy costs of over \$276 million in 2002. In the state of California, there were 48 frozen fruit and vegetable processing plants that consumed approximately 330 million kWh of electricity (Hackett, Chow, and Ganji 2005).

Most of the electricity consumed by these plants is used for their ammonia refrigeration systems. Other electrical loads include lighting, compressed air systems, hydraulic pumps and other process drive motors.

In fruit and vegetable processing plants, there may be several ammonia refrigeration systems. These systems support various evaporating temperatures, including 1.7°C (35°F) for water chilling, -21°C to -18°C (-5°F to 0°F) for frozen storage and -40°C to -32°C (-40°F to -25°F) for quick freezing.

Seven fruit and vegetable processing plants were analyzed, with energy consumption ranging from 37.1 million kWh per year for the largest plant to 4.8 million kWh per year for the smallest plant. It was found that the large facilities included very large ammonia refrigeration systems that included newer, more efficient compressors and evaporative condensers as well as better controls while the small facilities generally had several ammonia refrigeration systems dedicated to a particular part of the production process and these systems tended to be old and lacked centralized instrumentation and monitoring equipment (Hackett, Chow, and Ganji 2005).

In their investigation, Hackett et al. (2005) found that a major cost savings could be achieved by changing from a timer-based defrost control to a more energy efficient demand-based control. In addition, major savings could also be realized by allowing the system head pressure to float with the outdoor air wet-bulb temperature. Retrofitting single-stage systems to two-stage

systems and refrigerant subcooling in two-stage compression systems were also found to save considerable energy. Simple measures such as increasing the insulation thickness on pipes, vessels and cold storage rooms as well as reducing infiltration of warm, moist air into the refrigerated spaces was found to be effective in reducing energy costs. All of these upgrades has a simple payback of one or two years.

High efficiency lighting retrofits were found to have low to medium impact on energy savings with a simple payback of approximately two years (Hackett, Chow, and Ganji 2005). Typical recommendations for the seven audited plants included the use of occupancy sensors, daylight sensors and bi-level lighting controls on high-intensity discharge (HID) lighting fixtures. In addition, it was recommended that T12 fluorescent, incandescent, and halogen lighting be replaced with high efficiency T8 and T5 fluorescent fixtures, compact fluorescent lamps and metal halide lighting.

Motor-related retrofits, including the use of variable frequency drives and replacing non-functioning standard efficiency motors with premium efficiency motors, was found to provide a moderate energy savings (Hackett, Chow, and Ganji 2005).

A significant demand and cost savings was found by shifting all or part of the cold storage refrigeration load to off-peak demand periods (Hackett, Chow, and Ganji 2005).

11.3 Energy Efficiency in Fruit Storage Warehouses

Fruit storage warehouses present an excellent opportunity for energy savings with a potential savings of 10 percent to 50 percent of total energy used at the facility (Wilcox 2001). Energy usage by the refrigeration system represents the majority of energy used by fruit storage warehouses and is the focus of energy conservation techniques. Peak energy usage typically occurs in the fall, when the warehouses are loaded with fruit from the harvest. As fruit is removed from each warehouse, the energy usage reduces and reaches a minimum during the summer months. The refrigeration systems are sized for pulling down the temperatures after the fall harvest. After this period, the systems are typically operated at part load and are frequently inefficient in this operation. Typical energy conservation measures for these facilities include computer control, reducing the minimum condensing pressure and VFDs for evaporator fans, condenser fans and screw compressors.

Computer controls can reduce energy usage by properly controlling VFDs, cycling evaporator fans, compressor staging, automated suction pressure optimization and smoother condensing pressure control (Wilcox 2001). An appropriate computer control system is essential to reducing energy usage while maintaining temperature control.

The minimum condensing pressure can be lowered during cool weather in the fall, winter and early spring to reduce energy usage. This is a period of time which fruit storage faculties experience high demands, allowing for substantial savings. Most systems should be able to operate at condensing pressures low as 80-90 psig with simple modifications to the refrigeration system.

Fruit storage warehouse refrigeration systems are sized for maximum load for pulling down the temperature of the fall harvest. After this period, evaporator fans, condenser fans and screw chillers are typically not required to operate at full load capacity. This presents the opportunity for energy savings by installing VFDs on motors in this equipment. Speeds can be reduced by as much as 50 percent, allowing for energy use reductions of up to 80 percent (Wilcox 2001).

Other common efficiency opportunities include lighting upgrades which include higher efficiency lamps with dimming capability and fast acting doors to reduce infiltration loads.

Additional energy conservation opportunities are available in new construction which can be cost prohibitive in existing facilities. Condensers with an efficiency of 300 MBH/hp or lower design condensing temperatures can be installed for higher energy savings. A diverse range of compressor designs and capacities can allow for optimal efficiency by allowing the system to match the load at high ratios. Premium efficiency motors can be installed on some loads and the incremental cost for a VFD is reduced due to savings from eliminating magnetic motor starters.

The above energy conservation strategies were implemented on five different fruit storage warehouses in the Pacific Northwest with refrigeration systems ranging from 193 hp to 1,448 hp. Total energy savings in these facilities was reduced by 21 percent to 47 percent with a resulting simple payback ranging from 3.0 years to 6.2 years. If utility incentives available to the owners are included, the resulting simple payback is between 1.5 years and 3.1 years for the facilities.

11.4 Reducing Evaporator Fan Energy Usage in Fruit Storage Warehouses

Two evaporator fan energy savings techniques were tested by Hellickson and Baskins (2001) in two controlled atmosphere (CA) fruit storage rooms and compared to traditional continuous fan operation. The two rooms stored D'Anjou pears, with Room #1 holding approximately 1,120,000 pounds of fruit while Room #2 held approximately 946,000 pounds of fruit. Each room had one Krack evaporator unit with four 30-inch diameter fans, each powered by a 2 hp fan motor. The evaporators had four fins per inch and a rated cooling capacity of 23 tons of refrigeration and a total air circulation of 50,700 cfm.

The traditional mode of operation was to have all four evaporator fans operating full-time and the room set point temperature at 30°F. The first evaporator fan energy savings technique studied was to turn off two of the 4 fans on the evaporator and maintain the room set point temperature at 30°F. The second technique studied was to keep two evaporator fans off and cycle the other two evaporator fans at 2 hours on and 2 hours off during operation with the room set point temperature reduced to 29.7°F. One defrost period was scheduled per day in each room. The temperature, humidity and CO₂ levels were monitored during the test, with a random selection of fruit being weighed before and after the study to evaluate weight loss.

With two evaporator fans turned off, the refrigerant temperature dropped to maintain the room set point temperature. The room containing more fruit experienced icing of the evaporator

between defrost events and a cyclic decrease of 1.5°F in refrigerant temperature and corresponding cyclic decrease in room humidity between defrost events. The refrigerant temperature and room humidity were stable in the room with less fruit. The fruit furthest away from the evaporator, in the room containing more fruit, experienced a 0.5°F temperature increase. The CO₂ levels in both rooms were unaffected by the reduced fan operation. Using this technique, energy usage by the evaporator fans decreased from approximately 1,000 kWh per week to 500 kWh per week in each room, as shown in Table 12.

Table 12: Evaporator Fan Energy Usage.

Source: (Hellickson and Baskins 2001)

	Room #1	Room #2
Amount of Fruit in Room	1,120,000 pounds	946,000 pounds
Mode 1: 4 fans continuous	974 kWh/week	993 kWh/week
Mode 2: 2 fans continuous	501 kWh/week	520 kWh/week
Mode 3: 2 fans on/off	264 kWh/week	260 kWh/week

The second technique consisted of leaving two evaporator fans off and cycling the other two fans at 2 hours on and 2 hours off, with the room set point temperature reduced to 29.7°F, 0.3°F lower than the previous tests. The CO₂ levels when cycling the fans increased by 0.02 percent in each room. Fruit temperatures in bins on the floor in both rooms increased 0.5°F then stabilized during fan cycling. Using this fan cycling technique, reduced weekly energy usage by the evaporator fans from approximately 500 kWh to 260 kWh, as shown in Table 12.

The temperature and humidity variations recorded during these tests were not considered sufficient to negate the energy savings of fan cycling (Hellickson and Baskins 2001). One possible way to reduce the temperature variation of the fruit during evaporator fan cycling would be to improve air distribution within the room.

11.5 Improving Efficiency of Aging Refrigeration Systems

Older refrigeration systems can be upgraded to provide improved energy efficiency with quick paybacks (Wilcox 1997). These older systems often contain electro-mechanical controls and lack compressor unloaders and variable speed drives. Systems containing reciprocating compressors can often benefit from the installation of four key components: computer controls, compressor unloaders, liquid pressure amplifiers (LPAs) and variable speed drives. Liquid pressure amplifiers (LPAs) are small pumps installed on the liquid line between the condenser outlet and TXV to prevent the flashing of R-22 at low pressures. With LPAs installed, a system can be operated at higher suction pressures and lower discharge pressures to reduce compressor power and increase system capacity. Following are two case studies demonstrating these improvements.

A distribution center in Oregon stores chocolates, fruit, and flowers in cold storage and freezers. The facility contains four reciprocating R-22 compressors totaling 400hp that serve a single suction group. An energy audit of the facility resulted in the implementation of computer

controls and data loggers, the addition of unloaders on the existing compressors and the installation of 11 VFDs for the evaporator and condenser fans. The compressor unloaders installed were an optional upgrade to the existing compressors and utilized factory components. The unloaders allowed the system to more accurately target the desired suction pressure and allowed flexibility in sequencing compressors to avoid excessive starts. The energy conservation measures saved the facility 900,000 kWh per year, a 45 percent reduction in refrigeration energy usage, with a resulting simple payback of 4.6 years (Wilcox 1997).

A fruit storage facility in Oregon sorts, boxes and holds apples picked from the surrounding area. Three engine rooms fitted with reciprocating compressors were upgraded. One of the engine rooms contained both an R-22 refrigeration system and an ammonia system. The other two machine rooms housed R-22 systems. Computer controls were implemented on all three engine rooms. In Engine Room #2 and #3, one compressor was retrofit with electric unloaders to allow desired sequencing and suction control. Evaporator fans were retrofitted with VFDs or computer controlled fan cycling to reduce energy usage. All condenser fans received VFDs and the R-22 systems received LPA pumps. These changes allowed the systems to more accurately control fan energy usage and suction and discharge pressures. The energy usage was reduced by 285,000 kWh per year, a 41 percent reduction in refrigeration energy usage, resulting in a simple payback of 5.3 years(Wilcox 1997).

As demonstrated, older systems can be retrofitted with simple changes for energy savings. The studies above each show a refrigeration energy reduction of over 40 percent (Wilcox 1997). Many other older refrigeration systems could benefit from the installation of compressor unloaders, computer controls, VFDs, and LPA pumps.

11.6 Coldstore Engineering in New Zealand

Refrigerated food storage facilities require impermeable and cleanable internal surfaces. Thus, sheet material facings, such as steel or laminates, fixed to the internal surfaces of the insulation material have been traditionally used. The structural sandwich panel systems first used in the late 1960s are the predominant construction method today (IPENZ 2009).

Prior to designing a refrigerated storage facility, the type of product to be stored and the handling system must be identified. Different food products have specific temperature and humidity storage requirements as well as handling and hygiene regulations. Also, the type of product will dictate the interface between the transport vehicles and the storage facility loading requirements (IPENZ 2009).

Reciprocating compressors can be used on medium to large refrigeration systems and are compatible with all refrigerants. They are efficient but are limited in pressure range and require high levels of maintenance. Screw compressors can be used on medium to large refrigeration systems and are compatible with all refrigerants. They can operate over a wide pressure range but have poor efficiency when operated under partial load conditions. The use of variable speed drives can improve the part-load efficiency of screw compressors. In addition, screw compressors are reliable and require low levels of maintenance (IPENZ 2009).

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